Studies on the diversity and ecology of zooplankton population in Sundarban Estuarine System (SES), West Bengal, India.

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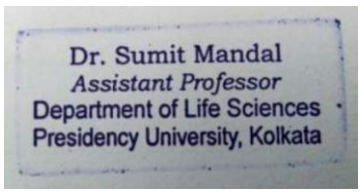

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Contents

Sl No.	Description	Page No.
1	Abstract	4
2	Introduction	5
3	Objectives	6
4	Study Area	6
5	Methodology	6-8
6	Results	8-16
7	Conclusions/Discussions	17-18
8	References	19-20
9	Figures and Tables	21-34
10	Plagiarism certificate	35
11	Certificate of conference attended	36-39
12	Published Manuscript	40-42

Summary of work

Title: Studies on the diversity and ecology of zooplankton population in Sundarban Estuarine System (SES), West Bengal, India.

1. Abstract

Diversity and community structure of zooplankton population has been assessed from a mangrove dominated estuarine complex, Sundarban Estuarine System India. The present work was designed to decode the effect of unusual precipitation during the monsoon season on zooplankton assemblages along with different hydrological parameters. The abundance of zooplankton was documented as lower during early compared to later monsoonal phase. Altogether, 56 zooplankton taxa were identified with copepods forming the predominant population. Regarding larval composition, the present study revealed that water quality plays an important role in the seasonal sharing of copepod larvae as well as different meroplankton larvae. Additionally, we analysed the community structure of zooplankton assemblages and their spatio-temporal variations based on different multivariate statistics and indicator value analysis. Zooplankton samples and environmental data were obtained seasonally and spatially from river Matla. Seasonal occurrence of dominant zooplankton taxa with high *IndVal* index was noticeably observed and it might be used as potential bioindicator for particular season and environmental condition in this estuarine system. Moreover, it is a maiden approach focussed on identifying indicator species of different zooplankton taxa at different time-scales. Exclusive occurrence of warm water species indicated the area is under threat of climate change mediated temperature rise. Different time series observation was also conducted to understand the specific diel and tidal variations of economically important shellfish larvae. The present study is a pioneering attempt to decipher the diel and selective tidal migration patterns of different larval stages of penaeid prawn, especially the *Metapenaeus dobsoni by* selecting spring and neap phase of the tidal cycle. It has been established that the early developmental stages of most penaeid prawns and crabs utilize the tidal currents for their ingress and egress mechanisms in order to travel horizontal distances or remain in their preferred habitats. Furthermore, the effect of climate change mediated elevated temperature on the physiology of the postlarvae of most economically important marine shrimp, *Penaeus monodon* from Sundarbans Estuarine System has been assessed. The present study has shown that postlarvae of *P. monodon* exposed to elevated temperature are not able to survive, although their physiological performances are significantly affected.

2. Introduction

Zooplankton plays a pivotal role in marine ecosystem functioning by transferring energy from primary producers to higher trophic levels (Mauchilne, 1998). Any subtle changes in the zooplankton community might have profound repercussion for higher trophic level. Marine zooplankton includes diverse species that form the basis of a healthy food web in estuarine ecosystem (Degerman et al., 2018). Recent studies have highlighted that zooplanktons play a key role in utilization of carbon produced by the microbial loop and also control the CO_2 system of the aquatic environment (Champalbert and Pagano 2002; Sommer and Stibor 2002). The role of zooplankton as secondary producer in marine and estuarine ecosystems makes them ideal candidate in estimating coastal fisheries. Due to their species diversity and different tolerance to the natural stress, they are often being used as the ecological indicators for the physical, chemical and biological processes in the marine ecosystem (Uriarte and Villate, 2004; Longhurst 2007). Nevertheless, knowledge of the zooplankton community is also fundamental in understanding the biogeochemical cycles and energy flows of marine food web because of its essential roles in the biological pump (Giering et al., 2014; Mitra et al., 2014).

Furthermore, estuarine environment is one of the vital habitats in the costal ecosystem and act as a nursery ground of many economically important organisms. Interannual fluctuations of zooplankton composition as modulated by hydrographic alteration have been noticed in several estuarine habitats globally. However, knowledge about seasonal succession of zooplankton community and the complex interplay between environmental parameters has never been explored systematically from Sundarban Estuarine System (SES). In the SES, knowledge about the diversity and ecology of zooplankton with respect to water quality parameters are relatively meagre, though some studies have been conducted on the western sector of Sundarbans (Bhattacharya et al. 2014a, b and 2015; Sarkar et al. 2007).

Studies of zooplankton could provide precious information on biological production potential of SES and changes in water quality may directly affect the abundance and composition of zooplankton population. The aim of the present work is to identify indicator species of zooplankton community, their seasonal succession pattern, diel variation of meroplankton and determine the hydrological drivers in regulating the community structure. To evaluate the changes in zooplankton population dynamics associated with natural environmental variables, a seasonal observation over a spatial scale and tidal observation are utmost important.

3. Objectives

The main objectives of the proposed study are:

i. To study seasonal changes of surface water biogeochemistry (temperature, salinity D.O., pH, alkalinity, nutrients, SPM, turbidity, chlorophyll *a* etc.) in the suitable sites.
ii. To ascertain spatial and temporal variation in zooplankton communities along the study area.
iii. To understand the physicochemical factors influencing distribution patterns of zooplankton communities.
iv. To study the Selective Tidal Stream Transport (STST) with emphasis on economically important shellfish larval population.
v. To understand the impact of climate change on meroplankton species by conducting mesocosm study.

This study will generate a high quality database of zooplankton species and economically important shellfish larval population along with environmental parameters of a mangrove dominated coastal area.

4. Study area

The Indian Sundarban Estuarine System is a mangrove dominated macrotidal estuarine complex of the river Ganges, situated at the northeast coast of the Bay of Bengal. The area experienced subtropical monsoon climate with huge precipitation and several cyclonic storms. This unique bioclimatic zone is well-known for its species variety, including numerous taxa of phytoplankton, zooplankton, microbes, benthic organisms and fishes (Gopal and Chauhan, 2006). According to the objective of present research, spatio temporal measurement of zooplankton and hydrological parameters were carried out at river Saptamukhi (Western part) and Matla (Central and eastern part) in Sundarban. The map of the sampling location along with study stations for entire research work has been plotted in Fig. 1.

5. Methodology

5.1 <u>Objective 1,2 and 3</u>

5.1.1 Sampling strategies

To investigate the intra-monsoonal changes in zooplankton population with physicochemical variables, the first sampling was done in the month of July and September 2013 at river

Saptamukhi (western part of SES) covering 15 study stations (S1-S15). Furthermore, to understand the spatio-temporal variation of zooplankton as well as different water quality parameters, seasonal sampling was done during four sampling periods (monsoon, winter, spring and summer) from 8 selected study stations at river Matla (M1-M8) eastern part of SES during 2016-17.

5.1.2 Collection and analysis of water quality variables

To understand the spatio-temporal variation of surface water biogeochemistry, water sample was collected from selected study stations during different sampling period. A 5L Niskin's water sampler was used to collect the water for physiochemical parameters following standard protocol. Water temperature, salinity, dissolved oxygen (DO) and pH were measured in situ. Winkler's titrimetric method and argentometric method (Strickland and Parsons, 1972) were followed to determine the DO and salinity of the water, respectively. Water temperature and pH were measured with the help of mercury thermometer and the portable digital pH meter (Model: Orion star A3110, Thermo-Scientific) respectively. One portion of sample was filtered and stored in ice box immediately after collection for the analysis of different nutrients and pigments (Chl *a*) following Strickland and Parsons, (1972) and Grasshoff et al., (1999). Suspended particulate matter (SPM) was analysed according to the method of Grasshoff et al. (1999).

5.1.3 Collection and analysis of zooplankton samples

Zooplankton samples were collected with the help of plankton net by horizontal towing at surface layer of estuarine water from different sampling stations (for spatial variation), seasons (for temporal variation) and tidal time scales (for STST). Immediately after collection, the concentrated zooplankton sample was stored in plastic bottle and fixed with 10% buffered formalin for further analysis. Zooplankton sample was analyzed both qualitatively and quantitatively with the help of standard identification manual (Conway et al., 2003; Kasturirangan, 1963; Muthu et al., 1978; Yousif Al-Yamani et al., 2011). Biomass was determined by standard protocol as described in Bhattacharya et al. (2015).

5.2 <u>Objective 4</u>

5.2.1 Sampling strategies

One time series sampling was also conducted in September-2013 at a fixed station (Kaikhali, TS1) for 24 hours with 1hr interval at river Matla in SES. Shellfish larvae and water sample

was collected to investigate their diel and tidal variation in biological and physiochemical parameters. Moreover, to get a comprehensive understanding about the Selective Tidal Stream Transport of shellfish larval population in SES, two 72 hours time series observations were carried out at TS1 during two tidal phases (spring and neap tide) with a 3 hr interval in August-2014. The day and night phase were considered according to time of sunrise and sunset during the sampling time and indicated in figures and tables by shaded portion. The water level was measured using a standard tide gauge followed by Chatterjee et al. (2013).

5.2.2 Collection and analysis of water quality variables

Same as described in section 5.1.2

5.2.3 Collection and analysis of shellfish larval samples

Same as zooplankton collection, described in section 5.1.3

5.3 Objective 5

5.3.1 Mesocosm experiment

To understand the impact of climate change mediated temperature elevation on meroplankton population, a mesocosm experiment was conducted in laboratory condition. The post larval stage of the most economically important shellfish (*Penaeus monodon;* common name: Tiger prawn) in Sundarban was selected for model species to study the effect of elevated temperature on their physiological energetics. The sensitivity and resilience to elevated thermal treatments was investigated by measuring physiological energetics like absorption, respiration and excretion rates to quantify the Scope for Growth as well as changes in length, weight and survivality percentages. Sterilized plastic aquaria were used for mesocosm treatment with natural filtered seawater collected from Sundarban. The desired temperatures were obtained by immersing thermostat in water baths holding the experimental aquaria for the entire study period (4 weeks). The data was collected every week and different statistical analyses were performed to investigate the effect of temperature and duration of stress (number of days) on the physiological parameters mentioned earlier. The entire experiment was repeated twice to crosscheck and minimize the standard error of overall experimental procedure in laboratory condition.

6. Results

Objective 1, 2 & 3:

6.1 Intra-monsoonal changes of water qualities and their impact on zooplankton population at river Saptamukhi (Nandy et al. 2018).

The Sundarban Estuarine System always experiences a huge annual rainfall during the period of June-October due to the Indian summer monsoon. To understand the impact of monsoonal precipitation on the estuarine biogeochemistry, an intra-seasonal observation was done in 2013. We collected the water and zooplankton samples from 15 study stations in river Saptamukhi during early and later monsoonal phase. A clear intra-monsoonal variation in surface water qualities and zooplankton population dynamics has been documented during the study. The average salinity was recorded very high (22.13±5.16) during early monsoonal phase (EM) compare to later monsoonal phase (LM); due to the effect of freshwater inflow during monsoon. The DO was recorded 6.51-1.38 $mg.L^{-1}$ and 5.93-0.62 $mg.L^{-1}$ during EM and LM respectively. The three major micronutrients (nitrate, phosphate and silicate) were recorded higher during EM than in LM, moreover the major excretory product of aquatic organisms' i.e. ammonium-N was observed in higher concentration during LM compare to EM. The seasonal variations of 10 different water quality variables along with the biomass and abundance of zooplankton population have been described in Table 1. (Objective 1)

During the LM the total abundances and biomass of zooplankton were observed to be much higher than in EM (Fig. 2a and b). Copepods was contributed maximum in terms of total zooplankton population during both sampling periods howbeit, different larval stages contributed 50% and 7% of total population during EM and LM respectively (Fig. 3). Lower percentages of larval population during LM might be due to their replacement by mature copepods and other meroplanktonic groups. A total of 56 zooplankton taxa have been identified during the study period, where *Paracalanus parvus*, *Bestiolina similis* and *Oithona similis* were observed to be the most dominant species in both sampling periods (Table 2). A significant ($p \leq 0.05$) intra-seasonal variation of zooplankton and physicochemical parameters were observed during both the study periods. (Objective 2)

The monsoonal precipitation altered the entire estuarine complex both biologically and chemically. Moreover salinity and nutrients played the essential role in controlling the diversity and ecology of zooplankton population in this part of SES. (Objective 3)

6.2 Spatio-temporal variation of zooplankton community with respect to different hydrological parameters at river Matla (Nandy and Mandal, 2020)

Apart from western side of SES to get a complete picture about the zooplankton population eastern side of SES was also covered. The present observation was conducted on river Matla (situated at the central part of Indian Sundarban) by selecting 8 study stations according to different salinity gradient from north-south direction. The zooplankton of the River Matla in Sundarbans Estuarine System was analyzed in order to understand the response of zooplankton population to different levels of hydrological parameters (e.g. temperature, salinity, oxygen, turbidity, nutrients and phytopigments) and how do these parameters influence the seasonal succession pattern. Surface water sample was collected during four separate seasons: monsoon (September-2016), winter (December-2016), spring (February-2017) and summer (May-2017). Different hydrological parameters like temperature, salinity, secchi depth, DO, pH, Chl *a*, nutrients and SPM showed a broad range in their variability among study stations. The significant ($p \leq 0.05$) seasonal variations of all environmental parameters along with their ANOVA values are presented in Table 3. (Objective 1)

The mean zooplankton abundance was documented from 573±270 ind. m^{-3} (during spring) to 1616±1392 ind.m^{-3}(during winter). The highest density was observed at station 6 during winter (4185 ind.m^{-3}), however lowest value recorded during spring at station 6 (257 ind.m^{-3}) (Fig. 4). A total of 56 types of zooplankton taxa had been identified and copepod was found to be the most abundant zooplankton taxa, both quantitatively and qualitatively, than other taxonomic groups of zooplankton. They were represented by 36 species belonging to 4 orders. Calanoida documented as most dominant group comprising of 25 species followed by Cyclopoida (5 species), Harpacticoida (4 species) and Poecilostomatoida (2 species). Out of 36 species of copepoda recorded, only 8 species had been identified as most dominant during entire sampling period. These species are: *Acartia spinicaudata, Acartia* sp., *Bestiolina similis, Euterpina acutifrons, Labidocera acuta, Paracalanus aculeatus, P. parvus* and *P. indicus.* Among all seasons maximum shellfish larval population (ranges from 78±13 to 1269±84 ind.m^{-3}) was recorded during winter, especially at downstream stations of the river facing Bay of Bengal. However, minimum shellfish larval population was recorded during spring season (ranges from 56±8 to 219±44 ind.m^{-3}) (Fig. 5). The PERMANOVA analysis was performed to elucidate the major changes of zooplankton population. There were significant variation observed both spatially (F= 713.12, p=0.001) and seasonally

(F=150.66, p=0.001). Altogether the spatio-temporal (F=288.33. p=0.001) variations were found to be significant in the present study. (Objective 2)

The statistical relationship between the composition of zooplankton and the physicochemical variables were also analysed at different study stations. We used Canonical Correspondence Analysis (CCA) to investigate the relationship between physicochemical variables and zooplankton assemblages and two graphical plots are generated as station and species biplot (Fig. 6). The station biplot depicts the responsible environmental parameters for clustering different study stations during different seasons. The species biplot was done to investigate the role of environmental parameters on zooplankton species distribution. In this plot, distinct clusters and species association are formed depending on their preferable environmental conditions. The result of IndVal analysis demarcated altogether 10 species of copepod and 12 non copepod taxa which were found to be the major indicator species of different study seasons (Table 4). During monsoon, *Acartia* sp., *Oithona brevicornis, O. similis, O. simplex, Paracalanus. Parvus* were the indicator species for all study stations. However in winter, *A. clausi, L. minuta*, cyphonautes larvae, Gastropoda veliger, nauplius larvae, *Zonosagitta bedoti* and zoea larvae were found to be dominated and maximum *IndVal* index was encountered. *C. danae*, copepoda nauplii, calyptopis larvae, Echinodermata larvae and hydrozoans showed significant indicator species for spring season, but the high value of *IndVal* index documented for *Eucalanus* sp., *E. elongatus elongatus*, Ctenophora, *Belzebub hanseni* and shrimp larva during summer (Table 4). In the present investigation, the seasonal occurrences of particular zooplankton with significant temporal variation signify the variation of salinity and other environmental factors in the surface water exerts either a direct and/or indirect effect in the appearance or disappearance of some taxa and replacement by others. The Nonmetric Multi Dimensional Scaling (NMDS) also revealed that, the abundance of indicator zooplankton taxa varied seasonally and act as responsible factor for significant (p=0.001) dissimilarity among four sampling period (Fig. 7 and Table 5). The observed information is a stepping stone in formulation of baseline database on the zooplankton with reference to water quality parameters and highlights the importance of zooplankton as bioindicator community for further ecological assessment and formulation of policies regarding sustainable development at Sundarbans Estuarine System. (Objective 3) Representative pictures of some identified zooplankton taxa from SES have been presented in Fig. 8.

Objective 4:

6.3 Diel and tidal variation of economically important shellfish larval population in SES: Time series analysis.

Among zooplankton shellfish larval populations are regarded as one of the most important communities both ecologically and economically estuarine systems. Due to their limited ability for horizontal movement, the survival of these communities in an estuarine complex always depends on tidal flows and turbulence. The densely mangrove dominated monsoonal estuary like Sundarban is considered the best nursery ground for different shellfish populations. Moreover, the success of coastal shrimp landing depends on the survival of these standing stocks. In general, shellfish-larvae perform diel and tidally synchronised behaviours for successfully migrating to their preferred nursery grounds with changes in the horizontal water flow regime. This phenomenon is known as the Selective Tidal Stream Transport or, STST (Shanks, 1995; Forward and Tankersley, 2001). A behavioral mechanism for up-estuary migration by early larval stages involves selective tidal stream transport, in which larvae are up in the water column during high tides and low in the water column during falling tides or vice versa. Present investigation was done to explore the diel migration of shellfish larval population with respect to the tidal rhythm in SES.

First observation was carried out at 1h intervals for 26 hours during a peak monsoon season in 2013 at previously selected study station (TS1). Sampling was done to collect shellfish larvae and surface water qualities along with water level changes. The surface water physicochemical characteristics exhibited a significant diel variation during the study. There were 6 types (shrimp protozoea, mysis, post larvae, juveniles, crab zoea and megalopa) of shellfish larval population was identified with their endogenous tidal rhythm during day and night. Water temperature, salinity, pH, dissolved oxygen and micronutrients variations over the entire diel cycles were recorded and described in Table 6. The percentages of different larval composition are depicted in Fig. 9 and maximum shellfish larval population was dominated by penaeid shrimp larvae. Among shrimp larval population the post larval stages were most abundant (37%) followed by mysis (28%), protozoea (18%) and juveniles (14%).The zoea and megalopa stages of crab were recorded very lesser number in collected during day time, but was present in varying numbers during night collections.

The occurrence and abundance of shrimp larvae were significantly ($p \leq 0.001$) influenced by the tidal action, being comparatively more at nocturnal flood tide condition in surface water

of the estuary (Fig. 10). It has been established that the population density of different shellfish larvae varied remarkably with endogenous tidal rhythm.

Second observation was carried out for better understanding about the influence of tidal rhythm on different economically important shellfish larval community for a longer time scale. The time series observation was done in two different tidal phases (spring and neap tide) for 72 hours at TS1 station during August-2014 (selected as peak monsoon season at SES). The water and larval samples were collected every 3hours interval during two tidal phases and the influence of tide on diurnal variations of shellfish larvae have been established. Temperature and salinity variations over the entire diel cycles during two tidal phases have been more significant than other hydrological parameters (Table 7). The tidal amplitude as well as current velocity of surface water seems to influence the different larval population in the present investigation. 3 larval stages of shrimp and 2 larval stages crab have been documented as shellfish larval community. Their diel and tidal variations during two phases have been plotted in Fig. 11 a and b. Total shellfish larval density recorded from 2177 ind.$100m^{-3}$ to 2 ind.$100m^{-3}$ during spring phase, however the total larval population observed from 794 ind.$100m^{-3}$ to 8 ind.$100m^{-3}$ during neap phase.

Noticeable variations in the composition of different larval percentages during spring and neap phase have been documented and plotted in Fig.12a and b. Maximum shellfish larval density was predominated by crab zoea recorded 52% during spring phase. Moreover, the shellfish larval density was predominated by shrimp mysis (47%) during neap phase. A significant diel and tidal variation in the relative abundance of different shellfish larval populations have been documented (Table 8). The availability of shrimp mysis was recorded maximum at day time during both tidal phases; however their juveniles prefer night time for their migration and retention in the estuarine habitat and exclusively avoid the daytime high tide condition. The relative occurrences of crab zoea larvae were observed maximum during spring phase compare to neap and their abundances are much higher in day time irrespective of tidal period. Moreover, the crab megalopa larvae were documented in higher abundances during neap phase especially during the low tide condition. The distinct larval assemblages at different time scale have been well observed during both spring and neap phases, indicating the significant variability in their abundances along the specific diel and selective tidal stream.

6.4 Selective Tidal Stream Transport (STST) of *Metapenaeus dobsoni* during peak monsoon season at SES (Nandy et al. under review)

It has been well documented that the larval stages (mysis, post larvae, juveniles) of most penaeid prawns prefer the estuarine waters during their developmental phases and upon maturing further, egress out to the coastal waters. Studies about the abundance and distribution of postlarvae of *Penaeus monodon* have been conducted (Hoq et al., 2001) in the Sundarbans region. Although *Penaeus* sp. has been extensively studied and artificially reared, knowledge about *Metapenaeus dobsoni* is lacking in spite of its economic importance as it is abundantly found all over the coasts of India. However, very little information is available about the larval migration patterns of *M. dobsoni*, which is another predominant commercially important shrimp species from this region. The present study was done to decipher the diel and selective tidal migration patterns of different larval stages of *M. dobsoni* by selecting spring and neap phase of the tidal cycle through a time series (72 hrs) analysis during a peak monsoon season (August 2014) at station TS1. The result from the present study indicated that the larval abundance was remarkably influenced by diel as well as tidal actions (Fig. 13). During spring and neap tides, the larval abundance had been recorded from 2 to 418 ind.100 m^{-3} and 3 to 419 ind. $100m^{-3}$ respectively. The maximum larval abundance was observed at night (i.e. from 6pm to 3am) of neap tide irrespective of tidal amplitude, whereas during spring tides the maximum larval abundance was recorded at low tide condition irrespective of diel variations. Moreover, their different larval stages (mysis, postlarva and juveniles) were found to be intriguing with different diel and tidal periods (Fig. 14). The peak increase in the abundance of mysis stages always synchronized with low tides during the neap phase, whereas the peak increase of juvenile abundance synchronized with the ebb currents during the spring tide. The mysis stages use the neap tide to remain in the estuary until further development and the juveniles use strong ebb tides of the spring phase to egress from the estuary to the open sea. Two way ANOVA was performed to identify the significant variations between sampling time and different larval stages of *M. dobsoni*. There were no significant variation among sampling time (p=0.602, spring phase and p=0.371, neap phase) albeit the variation among different larval stages were found to be highly significant during both sampling periods with p=0.00079 and p=0.01523 during spring and neap phases respectively. Total larval populations were observed to be higher during selective tidal phases, and low surface currents. The overall percentages of different larval stages are also documented in Fig. 15 and considerable variations between the two tidal phases have been

observed. Juvenile stage was comparatively higher percentage (83%) during the spring phase followed by mysis (14%) and post larva (3%), as reflected in Fig 15a. Furthermore, the mysis stage dominates during the neap phase (61%) followed by juveniles (34%), and post larva (5%), Fig 15b. These unique combinations of their position indicate their behavioural pattern for retaining their position in the suitable estuarine habitat at SES.

Objective 5:

6.5 Impact of climate change driven elevated temperature on the post larvae of Tiger prawn (*Penaeus monodon*) (Nandy et al. under review)

Extreme climatic occasions, such as sudden heatwaves and warming of sea surface temperature are anticipated to be more predominant in forthcoming years due to global climate change. As ocean warming continues, the growth and physiological performance of marine species will be strongly impacted by elevated water temperature. The Indian Sundarban is one of the best nursery ground for different shrimp populations, as these meroplankton organisms need estuarine water to complete their bipartite life cycle. Moreover, a clear indication of temperature rise from last few years has been identified in Sundarban (Mitra et al., 2009). In the present study we have investigated the growth, survivality and physiological energetics of post larvae of *Penaeus monodon* (collected from Sundarban) in changing thermal environments. Following the acclimation period, active individuals were transferred to the aquaria (40×28×20 inches) in triplicates (each holding 25 larvae) per treatment with filtered seawater. We exposed the larvae to four different water temperatures, 28^{o}C (average habitat temperature) and elevated temperatures 30^{o}C, 32^{o}C and 34^{o}C for four weeks and changes in survivality, growth, length, weight, food consumption rate, respiration rate, excretion rate and Scope for Growth (SfG) were measured every week for four weeks. The details experimental set up and water qualities maintained during the mesocosm study have been described in Fig. 16 and Table 9. All experimental setup and physiological measurements were done according to standard method described in Soyel and Kumlu (2003), Zhang et al. (2009) and Baag et al. (2020). Random sampling of 5 larvae from each replicate treatment aquaria was done weekly to measure total length and weight. The physiological energetics were measured by randomly selecting three larvae from each replicates of the same treatment and considered its mean values as one observation. Likewise, five observation data were generated for each treatment on 1st, 2nd, 3rd and 4th weeks of the experiment.

Significant changes were observed in growth performances as well as physiological energetics during entire experimental period. The lowest survival rate (50%) of the shrimp larvae was attained at 34°C during 4th week; moreover, the changes in survivality percentages varied significantly with temperature ($p<0.05$) and duration ($p<0.05$) but not in their interaction (Fig. 17). The final body weight of shrimp larvae exposed to 28°C was significantly higher than that of larvae exposed to 30°C, 32°C and 34°C ($p\leq0.05$) (Fig. 18a). The total length (TL) of the larvae varied along the test temperatures and showed a gradient of $TL_{28}>TL_{30}>TL_{32}>TL_{34}$. Furthermore, a significant difference was also noticed in total length between temperature ($p<0.05$), duration ($p<0.05$) and their interaction ($p<0.05$) (Fig. 18b). Food consumption rate (Fig. 19a) and absorption rate (Fig. 19b) on control and elevated groups were significantly higher than moderately and highly elevated groups. Conversely, the respiration (Fig. 19c) and excretion (Fig. 19d) rate were also recorded much higher on moderate and high elevated temperature than that of control and elevated condition.

SfG remarkably varied with temperature ($p<0.05$), duration ($p<0.05$) and the interaction between them ($p<0.05$). Control and elevated groups showed positive values throughout the study with highest value (11.50±0.69) recorded at 28°C in 4th week. However, at highly elevated temperature (34°C) the negative SfG was documented till 3rd week of experiment and showed a slight positive value (1.47±0.61) at 4th week after cope up with this environment (Fig. 20). Overall, the length, weight, survivality percentages, food consumption rate were decreased, however respiration and ammonia excretion rate have been increased in elevated temperature treatments resulting in a negative SfG in stressful environmental (elevated temperature) condition. PERMANOVA results showed clear significant ($p<0.05$) variations in different physiological performances of shrimp larvae both in different temperature treatment, days of exposure and their interaction (Table 10). The present results express for the first time that in the predicted future seawater temperature conditions would potentially reduce shrimp population through negatively affecting survivality, growth and other physiological performances. This could threaten entire marine ecosystem through disrupting marine food web in future climate change scenario.

7. Conclusions/Discussion

The present study revealed a clear spatiotemporal change of different environmental drivers and their significant influence on zooplankton population in Sundarban estuarine System. It has been documented that the monsoonal precipitation changed the entire estuarine complex

both biologically and chemically. In addition salinity plays the major influencing driver in controlling community structure of different zooplankton taxa. The unusual heavy rainfall along with river discharge significantly affected the hydrodynamics of estuarine system, which have been reflected in diversity and distribution pattern of zooplankton.

A strong spatio-temporal variation of hydrological parameters has also been documented in river Matla, where water temperature, dissolved oxygen, salinity and nutrients play the crucial factors in structuring the zooplankton population. Different indicator taxa have been reported for the first time from Sundarban. The complete seasonal cycle was observed with a noticeable variation of copepoda population and recruitment of meroplankton community. Identifying the indicator species of zooplankton at diverse spatio-temporal scale might help to assess ecological understanding in the climate change driven hydrological regime for system like SES in future.

Along with intra-seasonal, seasonal and spatial observations, different time series analysis was also performed to know the influence of diel and tidal variation on shellfish larval population. Tide and current play a significant role in their availability at surface water during peak monsoon season. By using *Metapenaeus dobsoni* as a proxy, the present time series observation clearly indicated a distinct diel and selective tidal migration patterns of different larval stages. The unique availability of different larval stages of prawn and crab during spring and neap tide are clearly understood from the study, which would help local fisherman to identify the suitable time of catch seeds. The diel larval population and preferences of selective tidal phase with low surface current indicate their behavioral pattern for retaining their position in the suitable estuarine environment for desired period of time. Studies on such economically important shellfish larval population on a specific tidal migration would be very advantageous in terms of community structure and sustainable management of *M. dobsoni* seed population in Sundarban.

From the present field studies, the occurrence of warm water sustained species of zooplankton in Indian Sundarban clearly indicated a signal of climate change mediated temperature rise compare to last couple of decades. A mesocosm experiment was conducted to understand the impact of elevated temperature on growth, survivality and physiological responses of postlarvae of *Penaeus monodon*. Significant changes were observed in body conditions as well as physiological energetics with elevated temperatures. Growth, survivality, food consumption rate and absorption rate were noticeably decreased howbeit, respiration and excretion rate increased with elevated temperature resulting a negative Scope for Growth in adverse condition. The thermal stresses remarkably impact the physiological

performances and growth of shrimp larvae, which would potentially reduce shrimp population and affect the fishery industry. Moreover, if the current trend of global warming continues, it may jeopardize the survival of marine organisms and damage the ecosystem functioning in Sundarban Estuarine System.

Due to their role in marine food chain as well as serve as good indicator organisms zooplankton always play an important role in sustainable fisheries and aquaculture. So, present dataset would be a stepping stone in building a baseline database of zooplankton community and unraveling their succsessional pattern moduled by different water quality parameters. Furthermore, present study also highlighted the importance of zooplankton as bioindicator organism which would be helpful for future researchers working at Sundarban. Time-series analysis of shellfish larval population would help local fisherman to identify the suitable time of wild seed collection in SES. Moreover, considering the present trend of elevated temperature, summer might become even warmer in future decades and physiological changes in aquatic species like shrimp larvae recorded from present study are greatly relevant. Accordingly, if the larval stages of such economically important aquatic organisms are severally affected in future climate change scenario, estuarine ecosystem and fishery productivity may face extensive risk. The present study is a complex blending of taxonomy, biogeochemistry and physiological energetics of zooplankton from SES.

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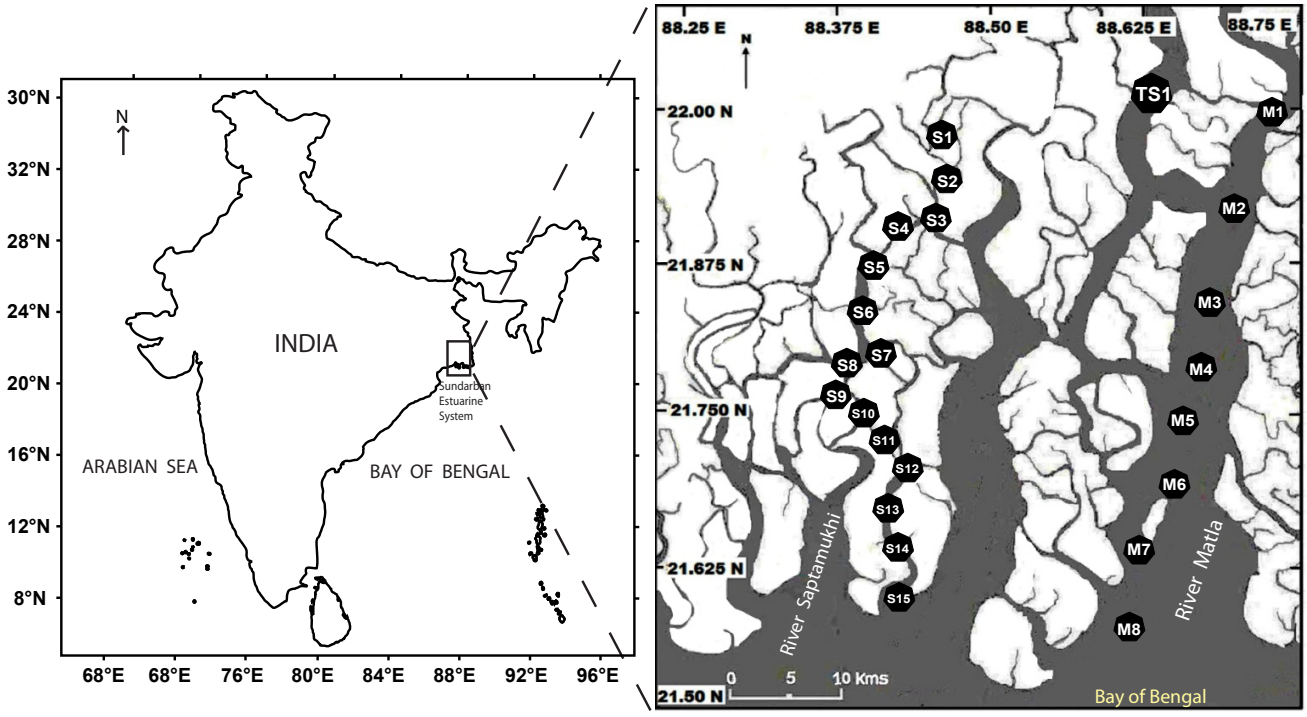


Fig.1 Map of the study area with sampling stations

Table 1. Intra-monsoonal variations of abiotic and biotic parametrs.

Parameters	Early phase of monsoon		Later phase of monsoon	
	Mean	SD	Mean	SD
Water temperature (°C)	30.13	0.87	31.82	0.50
Salinity	22.13	5.16	10.93	3.09
Dissolved oxygen ($mg.L^{-1}$)	6.51	1.38	5.93	0.62
pH value	7.33	0.36	7.09	0.38
Nitrite (µM)	1.37	1.82	1.76	0.81
Nitrate (µM)	19.24	2.72	12.48	3.72
Ammonia(µM)	0.27	0.24	1.21	0.21
Phosphate(µM)	1.48	0.18	1.12	0.48
Silicate (µM)	46.48	2.83	35.50	10.54
SPM ($mg.L^{-1}$)	335.93	287.56	100.92	128.32
Biomass($gm.m^{-3}$)	0.84	0.78	2.70	1.80
Zooplankton($Ind.m^{-3}$)	642	585	5481	4634

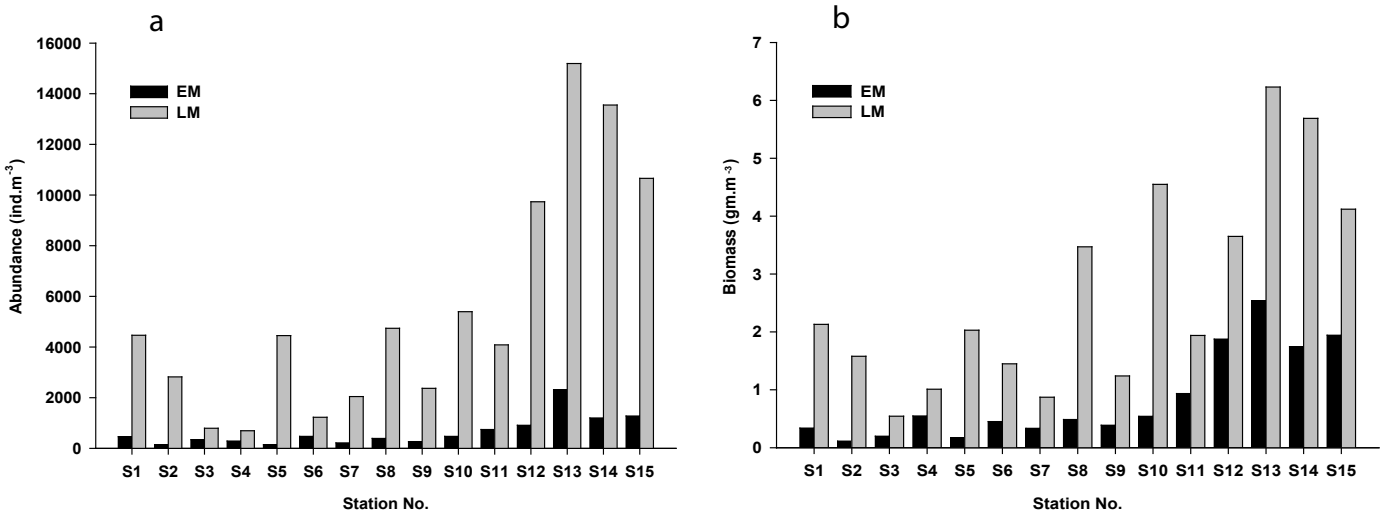


Fig. 2 Intra-monsoonal changes of total zooplankton a. abundance and b. biomass

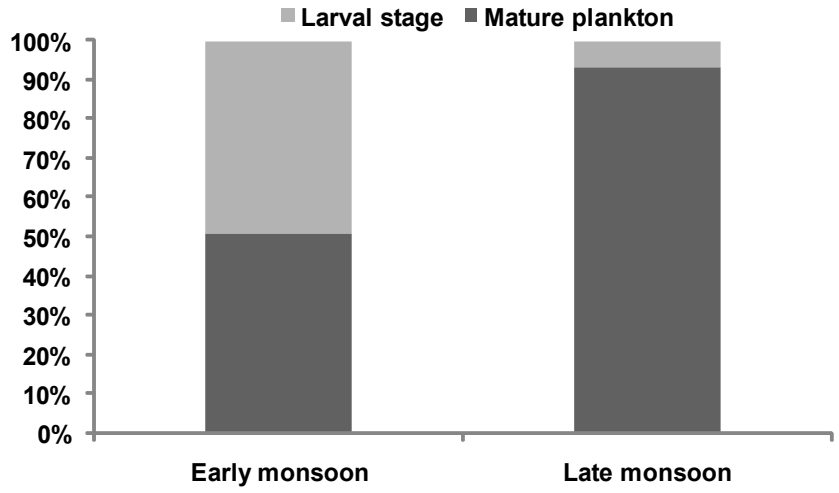


Fig. 3 The percentages of zooplankton population (larvae and mature stages)during two seasons

Table 2. List of identified zooplankton taxa and their seasonal occuarances at river Saptamukhi. '+'= present; '-'= absent

SL. No.	Name of zooplankton	Early phase of monsoon	Later phase of monsoon	SL. No.	Name of zooplankton	Early phase of monsoon	Later phase of monsoon
1	*Globigerina* sp.	+	-	29	*Oithona simplex*	+	+
2	*Tintinnopsis* sp.	+	-	30	*Paracalanus aculeatus*	+	+
3	*Obelia* sp.	+	-	31	*Paracalanus indicus*	+	+
4	*Oikopleura* sp.	+	-	32	*Paracalanus parvus*	+	+
5	*Acartia sewelli*	-	+	33	*Pseudodiaptomus serricaudatus*	-	+
6	*Acartia southwelli*	+	+	34	*Temora longicornis*	+	+
7	*Acartia spinicauda*	+	+	35	*Temora* sp.	+	+
8	*Acartia* sp.	-	+	36	*Temora turbinata*	+	+
9	*Acrocalanus gibber*	-	+	37	*Tigriopus fulvus*	+	-
10	*Acrocalanus gracillis*	-	+	38	*Lucifer penicillifer*	-	+
11	*Acrocalanus longicornis*	+	+	39	*Lucifer* sp.	-	+
12	*Bestionlina similis*	+	+	40	*Sagitta* sp.	+	+
13	*Calanus* sp.	-	+	41	Bivaive D-larvae	+	+
14	*Canthocalanus pauper*	+	+	42	Cirripede nauplius	+	+
15	*Clausocalanus* sp.	-	+	43	Copepod Nauplii	+	+
16	*Centropages* sp.	+	-	44	Cyclopoid copepod nauplii	-	+
17	*Euterpina* sp.	+	-	45	Cyphonautes larvae	+	-
18	*Labidocera acuta*	+	+	46	Echinoderm larvae	+	-
19	*Labidocera minuta*	+	+	47	Fish larvae	+	+
20	*Longipedia* sp.	-	+	48	Gastropod veliger	+	+
21	*Longipedia weberi*	+	-	49	Isopod larvae	-	+
22	*Microsetella* sp.	+	-	50	Nauplius larvae	+	+
23	*Macrosetella gracillis*	-	+	51	Onuphidae larvae	-	+
24	*Nannocalanus minor*	-	+	52	Polychaete larvae	+	-
25	*Oithona brevicornis*	+	+	53	Pontellid nauplius	-	+
26	*Oithona fallax*	+	+	54	Shirmp larvae	+	+
27	*Oithona nana*	-	+	55	Spionid larvae	-	+
28	*Oithona similis*	+	+	56	Zoea larvae	+	+

Table 3. Seasonal Mean and standard deviation (SD) of biogeochemical parameters of 8 stations. Asterisks denote significant differences.

Parameters	Monsoon		Winter		Spring		Summer		*(p values)*
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Temperature (^{o}C)	31.08	0.64	22.34	1.29	24.91	0.63	31.98	0.94	0.0001*
Secchi depth (cm)	37.50	13.09	39.38	12.66	55.00	7.07	20.13	7.22	0.0025*
Salinity	11.93	3.96	18.11	2.71	31.93	1.97	30.51	1.90	0.0057*
DO (mg.L^{-1})	6.56	0.80	5.73	0.40	5.03	0.57	4.77	0.13	0.0073*
pH	8.27	0.12	8.04	0.05	8.00	0.25	8.11	0.03	0.0001*
Nitrate-N (µM)	17.47	3.55	10.22	5.13	4.18	1.29	13.40	0.54	0.0221*
Nitrite-N (µM)	0.31	0.08	0.39	0.11	0.61	0.41	0.41	0.10	0.0188*
Phosphate-N (µM)	1.64	0.69	1.42	0.38	0.23	0.17	1.37	0.35	0.1131
Silicate (µM)	53.05	7.56	32.38	13.35	17.70	5.55	29.56	0.91	0.006*
Ammonium-N (µM)	0.35	0.11	0.17	0.11	0.30	0.09	2.32	0.65	0.0827
Chl-*a* (µg.L^{-1})	4.14	1.98	2.53	1.12	3.73	0.54	4.11	0.55	0.1820
Phaeopigments (µg.L^{-1})	0.50	0.47	0.46	0.44	0.18	0.15	0.45	0.20	0.0179*
SPM (mg.L^{-1})	54.90	48.06	162.44	95.98	27.38	9.16	261.18	96.68	0.0598
Zooplankton abundance (ind.m^{-3})	1202.88	768.38	1616.00	1391.01	573.38	270.22	951.38	482.40	0.0026*
Zooplankton biomass (gm.m^{-3})	2.68	1.48	3.28	1.87	1.88	0.61	2.69	1.35	0.0186*

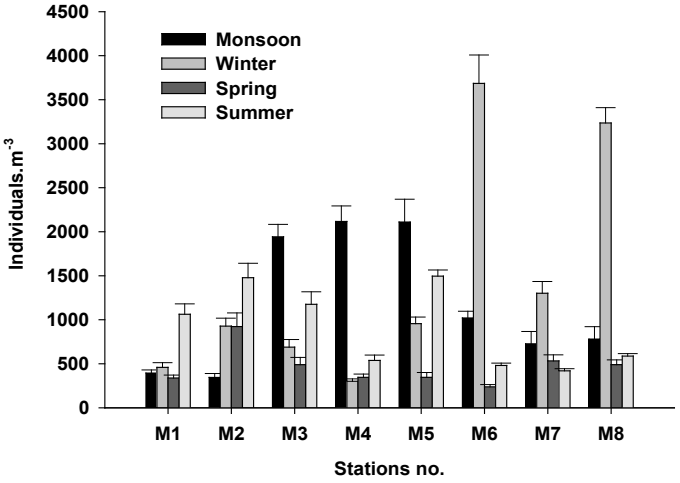


Fig. 4 Spatio-temporal variation of total number of zooplankton at river Matla

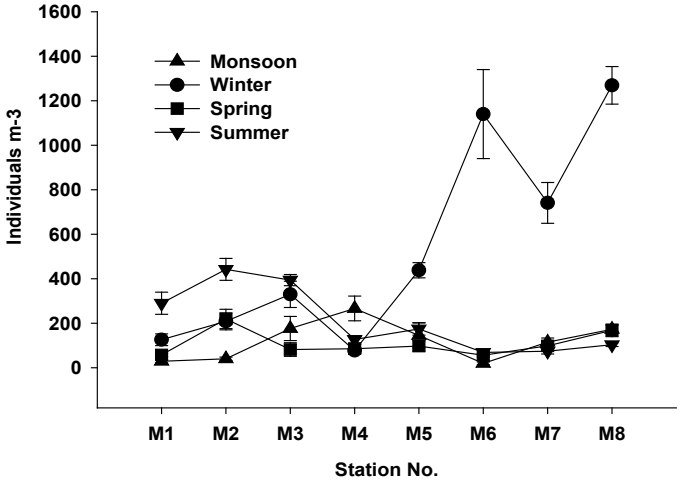
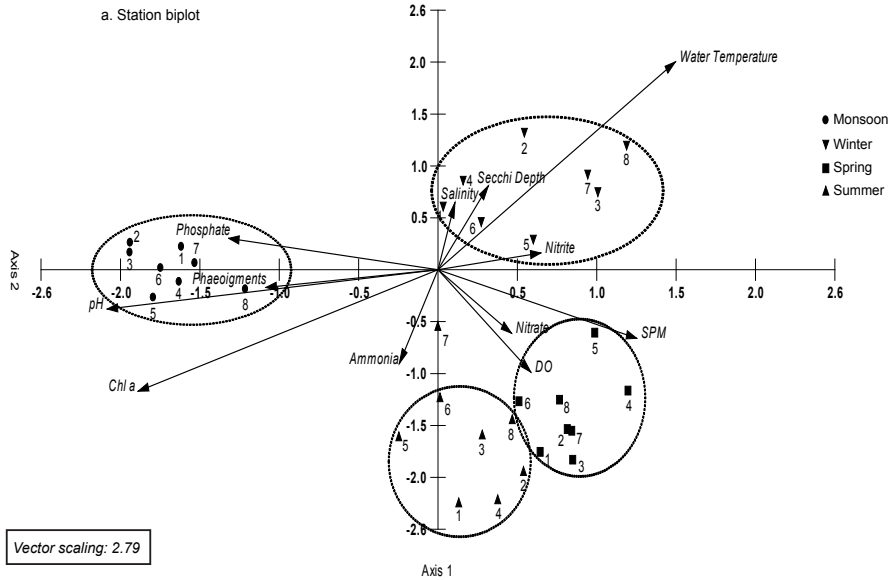


Fig. 5 Spatio-temporal variation of total shellfish larval abundance at river Matla



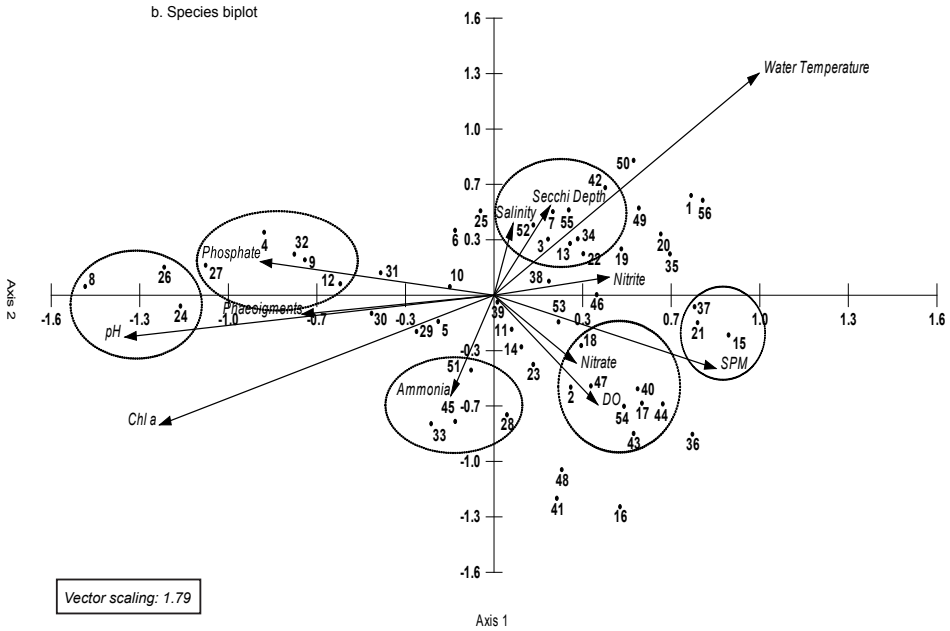


Fig. 6 Canonical Correspondence Analysis (CCA) analysis of zooplankton species with different environmental parameters and study stations. Species codes are described in Table 4.

Table 4. List of identified zooplankton taxa with their indicator values for each season. Bold values are considered major indicator species (*IndVal*>40, *p*=0.05)for the present study.

CCA code.	Name of Identified Zooplankton taxa	Monsoon	Winter	Spring	Summer
1	*Acartia (Acartiura) clausi* Giesbrecht, 1889	0	**74.47**	9.31	0
2	*Acartia (Acartia) danae* Giesbrecht, 1889	0	0	1.79	21.43
3	*Acartia (Acartia) negligens* Dana, 1849	0	32.29	0.69	1.04
4	*Acartia* sp.	**56.85**	6.05	1.21	0.41
5	*Acartia (Odontacartia) spinicauda* Giesbrecht, 1889	33.80	20.83	6.35	29.10
6	*Acartia sewelli* Steuer, 1934	6.82	32.95	0	0.85
7	*Acrocalanus gibber* Giesbrecht, 1888	0	12.5	0	0
8	*Acrocalanus gracilis* Giesbrecht, 1888	26.47	0	0	7.35
9	*Acrocalanus longicornis* Giesbrecht, 1888	**50**	0	0	0
10	*Bestiolina similis* Sewell, 1914	29.52	34.63	11.94	1
11	*Bomolochus* sp.	0	0	12.5	0
12	*Canthocalanus pauper* Giesbrecht, 1888	25	0	0	0
13	*Centropages* sp.	0	12.5	0	0
14	*Clytemnestra scutellata* Dana, 1848	0	0	12.5	0
15	*Corycaeus crassiusculus* Dana, 1849	0	20.46	**57.58**	5.68
16	*Eucalanus* sp.	0	0	25.68	**70.65**
17	*Eucalanus elongatus elongatus* Dana, 1849	0	7.72	30.39	**49.02**
18	*Euterpina acutifrons* Dana, 1848	0.3	9.52	20.83	22.32
19	*Labidocera acuta* Dana, 1849	1.09	38.43	12.5	12.5
20	*Labidocera minuta* Giesbrecht, 1889	0	**63.03**	26.89	6.3
21	*Labidocera* sp.	0	0	12.5	0
22	*Longipedia weberi* Scott A., 1909	0	19.11	5.88	0
23	*Microsetella norvegica* Boeck, 1865	0	0	0	12.5
24	*Oithona brevicornis* Giesbrecht, 1891	**83.01**	0	3.75	5.5
25	*Oithona nana* Giesbrecht, 1893	12.5	0	0	0
26	*Oithona similis* Claus, 1866	**91.3**	0.36	0	1.45
27	*Oithona simplex* Farran, 1913	**62.19**	0	6.1	0.61
28	*Oncaea venusta* Philippi, 1843	0	0	6.25	6.25
29	*Paracalanus aculeatus* Giesbrecht, 1888	34.45	26.72	7.84	27.17
30	*Paracalanus indicus* Wolfenden, 1905	36.02	17.72	0.2	16.54
31	*Paracalanus parvus* Claus, 1863	**45.94**	25.7	10.52	17.84
32	*Paracalanus* sp.	36.16	0	3.57	0
33	*Pseudodiaptomus serricaudatus* Scott T., 1894	0	0	0	37.5
34	*Subeucalanus subcrassus* Giesbrecht, 1888	0	25	0	0
35	*Temora discaudata* Giesbrecht, 1889	0	7.5	0.84	8.33
36	*Temora turbinata* Dana, 1849	0	0	2.78	29.17
37	Hydrozoa acrinulae	0	0	25	0
38	Arachnida	0	0	0	0
39	Bivalvia D larvae	26.16	34.77	7.95	26.16
40	Copepoda nauplii	0	17.63	**45.87**	13.46
41	Ctenophora	0	0	0	**62.5**
42	Cyphonautes larvae	0	**63.59**	2.17	1.63
43	Euphausiacea calyptopis	0	0	**62.5**	0
44	Echinodermata larvae	0	6.48	**55.55**	0
45	Fish larvae	2.5	0	5	30
46	Gastropoda veliger	8.52	**51.31**	12.12	26.84
47	Hydrozoa medusae	0	0	**62.5**	0
48	*Belzebub hanseni* Nobili, 1906	0	0	0	**87.5**
49	*Belzebub penicillifer* Hansen, 1919	0	21.4	1.78	0
50	Nauplius larvae (Cirripedia)	0	**82.8**	0.66	0
51	Polychaeta larvae	19.85	14.34	1.11	31.25
52	Pycnogonida	0	25	0	0
53	*Zonosagitta bedoti* (Béraneck, 1895)	9.87	**44.23**	16.59	28.85
54	Decapoda larvae	0	0	0	**87.5**
55	Star fish juvenile (Echinodermata)	0	37.5	0	0
56	Decapoda Brachyura zoeae	0.56	**71.19**	6.48	5.8

Table 5. Similarity Percentage (SIMPER) analysis for zooplankton assemblages formed by Nonmetric Multi-Dimentional Scaling (NMDS) considering each season: average dissimilarities (%) among season and Analysis of Smilarity (ANOSIM) results between two seasons are presented.

Seasons	Average dissimilarity (%)
Monsoon and Winter (ANOSIM, global R= 0.956, p =0.001)	55.46
Monsoon and Spring (ANOSIM, global R=0.997, p =0.001)	58.34
Monsoon and Summer (ANOSIM, global R=0.946, p =0.001)	50.13
Winter and Spring (ANOSIM, global R=0.742, p =0.001)	44.33
Winter and Summer (ANOSIM, global R=0.766, p =0.001)	46.06
Spring and Summer (ANOSIM, global R=0.628, p =0.001)	40.77

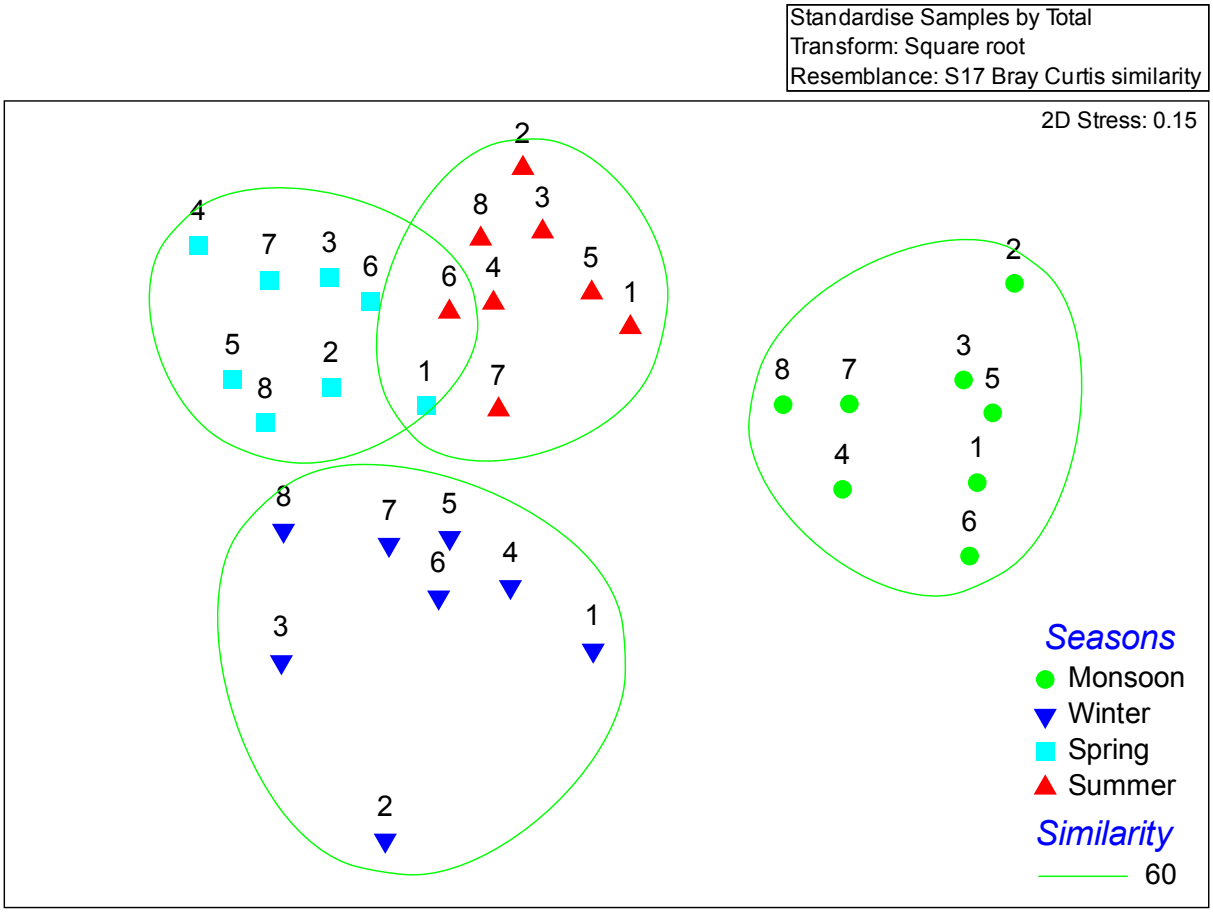


Fig. 7 Nonmetric Multi-Dimentional Scaling (NMDS) plot for seasonal zooplankton assemblages sampled in river Matla.

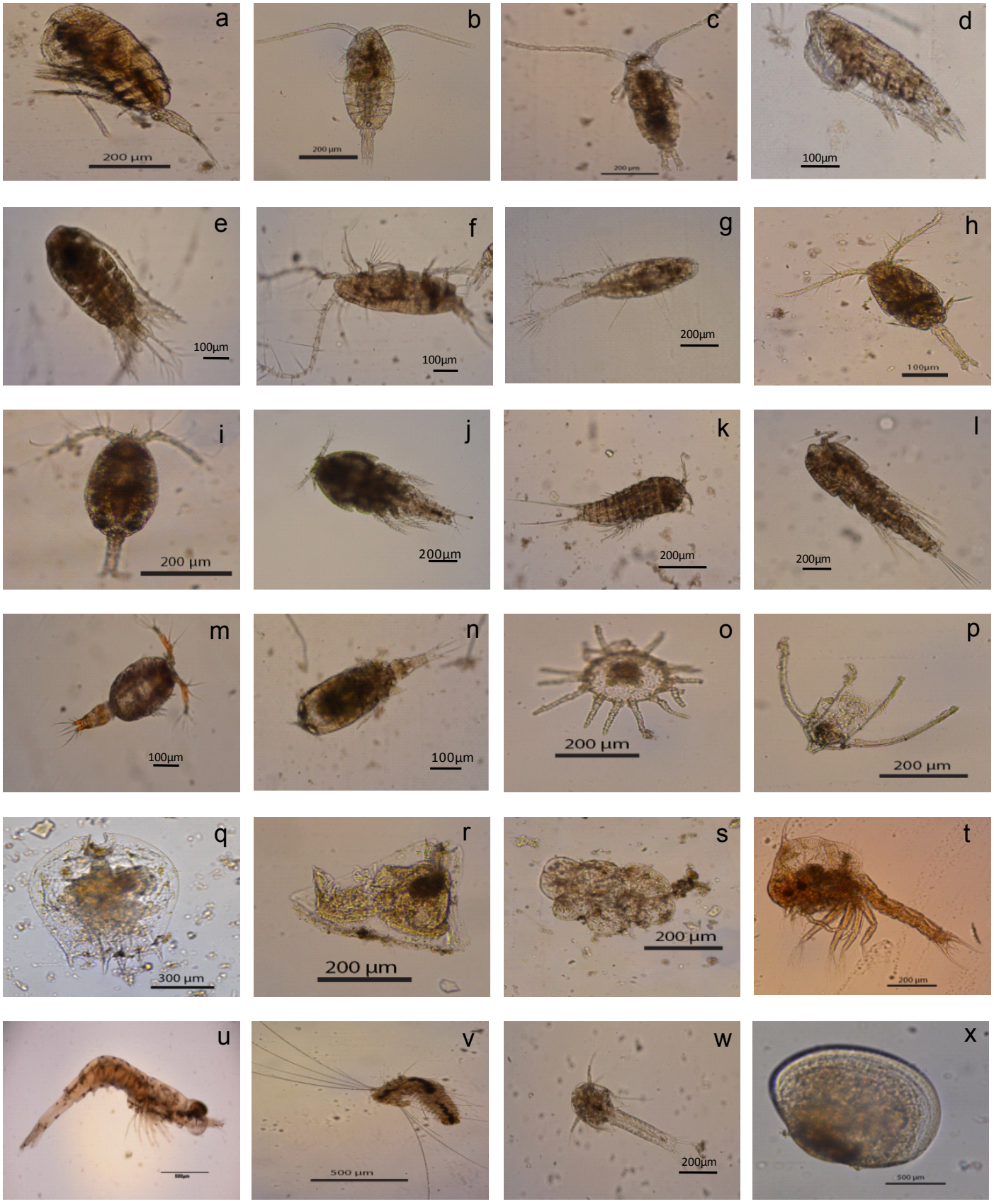


Fig. 8. List of identified zooplankton taxa during study; **a** *Paracalanus parvus*, **b** *Bestiolina similis*, **c** *Labidocera minuta*, **d** *Acrocalanus longicornis*, **e** *Temora discaudata*, **f** *Eucalanus* sp., **g** *Acartia sewelli*, **h** *Oithona similis*, **i** *Oithona simplex*, **j** *Longipedia weberi*, **k** *Microsetella norvegica*, **l** *Clytemnestra scutellata*, **m** *Oncaea venusta*, **n** *Corycaeus crassiusculus*, **o** *Obelia* sp., **p** Echinodermata larvae, **q** Ctenophora, **r** Cyphonautes larvae, **s** *Globigerina* sp., **t** Decapoda Brachyura zoeae, **u** Decapoda larvae, **v** Polychaeta larvae, **w** Euphausiacea calyptopis, **x** Bivalvia D larvae.

Table 6. Tidal variation of different hydrological parameters during the time series observation. Shaded portion indicate the night phase of the study period

Date	Time	Water level (m)	Water temperature (°C)	Salinity	pH	Dissolved Oxygen ($mg.L^{-1}$)	NO_3-N	NO_2-N	PO_4-P	SiO_2	NH_4-N
27-09-2013	03:00	2.04	31.50	14.91	8.31	5.81	12.50	0.73	1.41	31.38	1.05
27-09-2013	04:00	1.62	31.00	15.26	7.82	5.92	14.65	0.98	1.01	34.55	0.80
27-09-2013	05:00	1.20	31.40	15.26	8.00	5.70	20.66	0.46	0.79	31.92	0.95
27-09-2013	06:00	0.86	31.40	15.33	8.07	5.70	19.33	0.27	1.60	18.62	0.92
27-09-2013	07:00	0.66	31.80	16.33	7.33	5.70	14.26	0.89	0.48	20.99	1.35
27-09-2013	08:00	0.68	31.90	15.90	7.26	5.92	25.02	1.29	2.05	30.70	0.98
27-09-2013	09:00	0.92	32.00	16.04	8.27	5.48	16.26	1.22	0.58	48.92	1.08
27-09-2013	10:00	1.24	32.10	15.97	7.82	6.03	17.25	0.70	1.97	42.58	1.09
27-09-2013	11:00	1.60	32.50	15.97	8.30	6.25	15.25	0.91	1.89	21.59	1.49
27-09-2013	12:00	1.90	33.00	16.04	7.95	5.81	18.65	1.04	0.87	24.49	0.93
27-09-2013	13:00	2.12	33.00	15.83	7.57	5.81	18.15	0.37	1.44	40.76	1.54
27-09-2013	14:00	2.10	32.50	15.55	6.99	6.36	17.25	0.75	0.71	31.78	0.96
27-09-2013	15:00	1.86	31.00	15.62	7.33	6.14	13.65	0.30	0.54	41.36	1.24
27-09-2013	16:00	1.62	31.50	15.55	7.05	6.25	18.35	0.85	1.47	42.51	1.29
27-09-2013	17:00	1.34	31.20	15.40	7.39	6.90	14.65	0.31	0.80	28.48	1.15
27-09-2013	18:00	1.04	30.00	15.33	7.71	6.25	16.55	0.37	1.47	40.96	1.20
27-09-2013	19:00	0.80	30.00	14.34	7.48	6.25	17.21	2.20	0.64	38.19	1.10
27-09-2013	20:00	0.62	30.10	15.83	7.23	6.14	21.37	0.66	1.12	24.63	1.14
27-09-2013	21:00	0.76	29.00	15.97	8.16	5.81	20.55	2.16	1.41	37.38	0.97
27-09-2013	22:00	1.04	30.00	16.04	8.38	6.03	19.90	1.56	0.67	25.44	1.11
27-09-2013	23:00	1.44	30.10	15.90	7.76	5.70	15.46	1.40	1.06	29.42	0.89
28-09-2013	00:00	1.76	30.10	15.62	8.15	6.14	20.33	0.55	1.60	34.41	1.33
28-09-2013	01:00	2.06	31.20	15.55	7.80	6.03	21.03	0.91	1.35	24.22	1.14
28-09-2013	02:00	2.18	31.00	15.40	7.42	6.14	18.65	0.37	0.93	33.06	0.97
28-09-2013	03:00	2.10	30.50	15.26	7.38	6.36	19.00	1.00	0.80	47.57	0.97
28-09-2013	04:00	1.92	30.00	15.33	7.36	5.81	19.37	0.53	1.51	42.31	1.03
28-09-2013	05:00	1.70	29.50	15.33	7.19	6.14	20.01	1.16	1.41	57.22	0.88

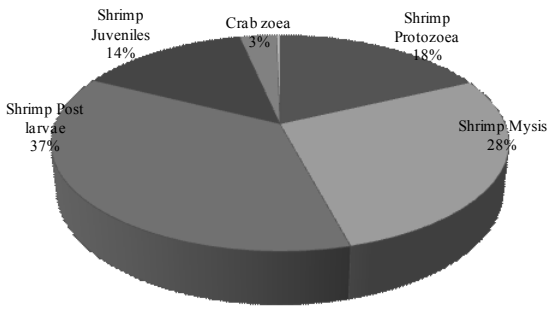


Fig. 9 Composition of different shellfish larval population

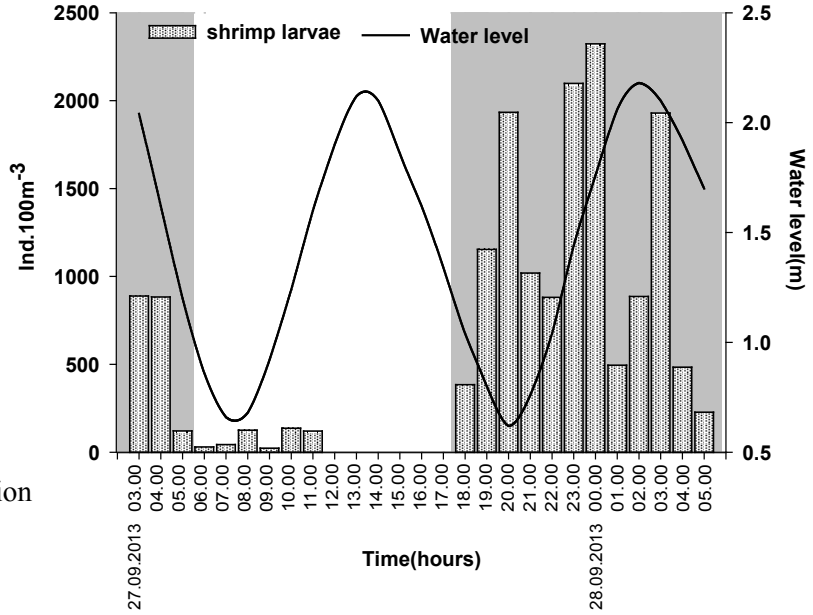


Fig. 10 Diurnal variation of shrimp larval abundance with water level. Shaded portion indicate the night phase.

Table 7. Diurnal variation of different hydrological variables during two tidal phases of the study periods

Parameters	Spring phase				Neap phase			
	Day Time		Night Time		Day Time		Night Time	
	Max	Min	Max	Min	Max	Min	Max	Min
Water level(m)	5.50	0.80	5.26	0.48	4.88	1.12	4.62	1.26
Current velocity(m.s^{-1})	3.78	0.44	4.17	0.26	2.20	0.12	2.73	0.20
Water temperature(C)	31.00	30.00	30.50	30.00	30.50	28.50	30.50	28.50
Dissolved Oxygen (mg/l)	5.60	4.63	5.39	4.42	5.17	3.34	5.39	2.80
Salinity(psu)	23.83	19.59	23.72	16.54	22.32	16.24	22.17	11.44
pH	7.68	6.39	7.68	6.67	7.48	6.45	7.52	6.66
Chlorophyll-a(µg/lit)	3.68	0.78	2.20	0.13	3.86	0.67	3.53	0.17
Nitrite-N(µM)	9.20	1.26	14.98	1.15	3.56	0.96	3.72	0.84
Nitrate-N(µM)	31.76	12.75	26.12	13.31	41.08	12.71	41.95	21.75
Ammonium-N(µM)	1.70	0.26	1.74	0.18	1.68	0.02	3.01	0.04
Phosphate-P(µM)	5.65	0.96	1.47	0.92	0.11	0.02	0.15	0.03
Silicate (µM)	38.39	15.72	40.20	15.07	137.28	37.06	78.66	29.31

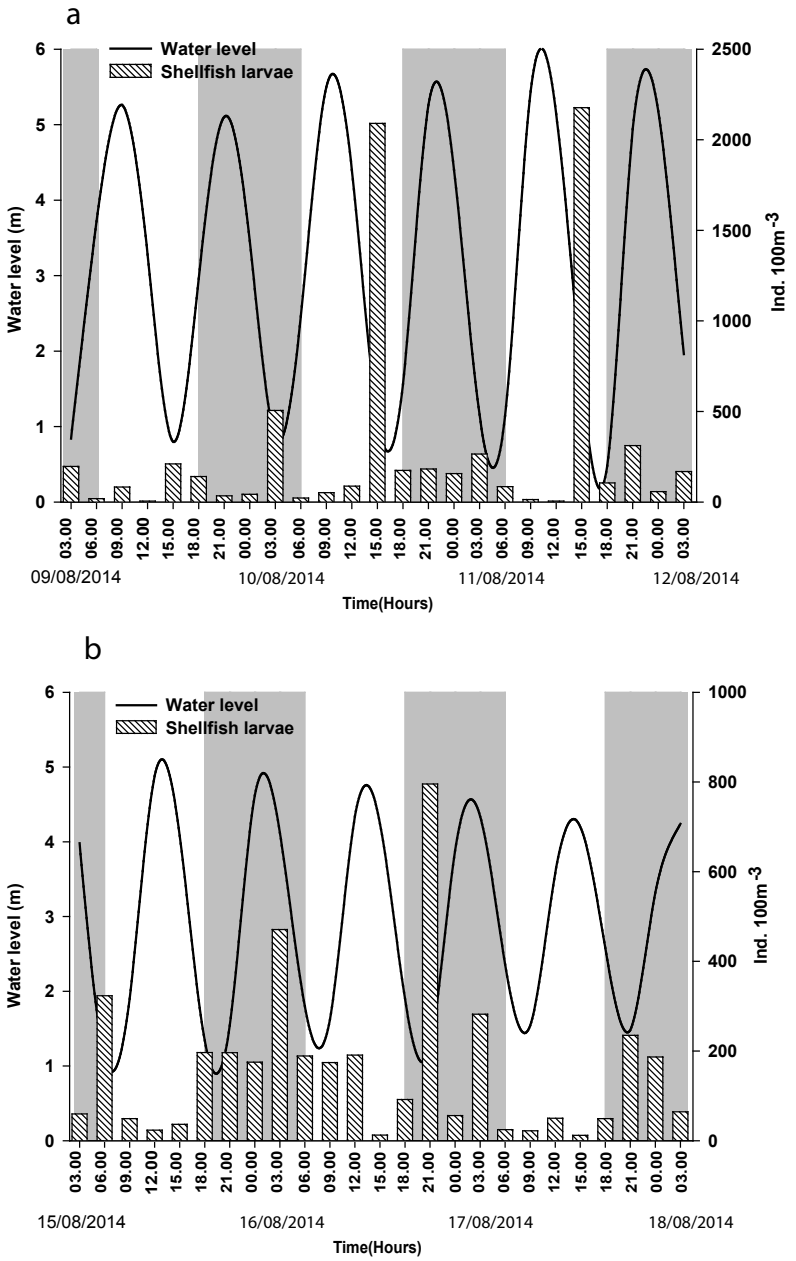


Fig.11 Tidal variation of shellfish larval abundance. a= spring phase and b= neap phase. Shaded portion indicate the night phase.

Table 8. Relative abundance (%) of shellfish larval population during different diel and tidal periods.

	Spring				Neap			
	High		Low		High		Low	
	Day	Night	Day	Night	Day	Night	Day	Night
Shrimp Mysis	54	10	2	23	81	36	35	55
Shrimp Post larvae	9	8	0	4	5	9	6	6
Shrimp Juveniles	0	43	23	48	0	47	8	17
Crab Zoea	35	15	74	9	0	3	0	1
Crab Megalopa	2	24	1	16	14	5	51	21

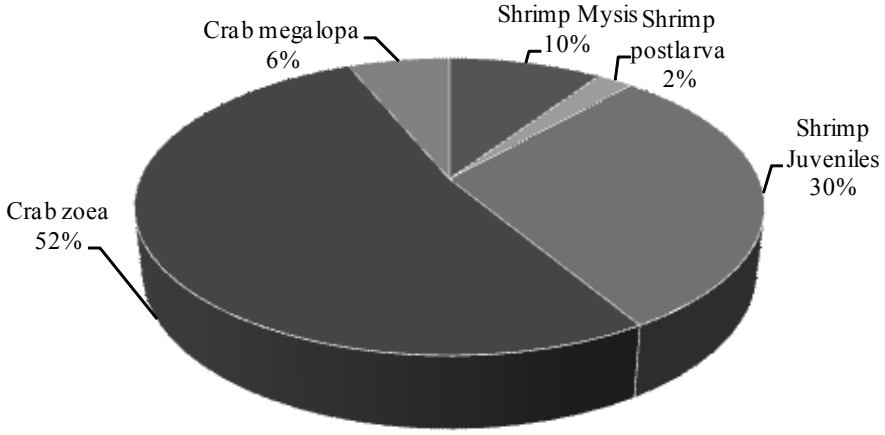


Fig. 12a Shellfish larval composition during spring tide

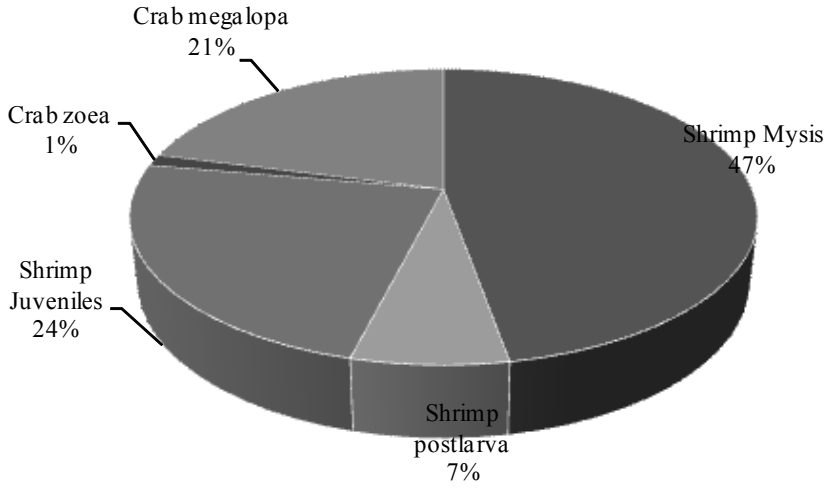


Fig.12b Shellfish larval composition during neap tide

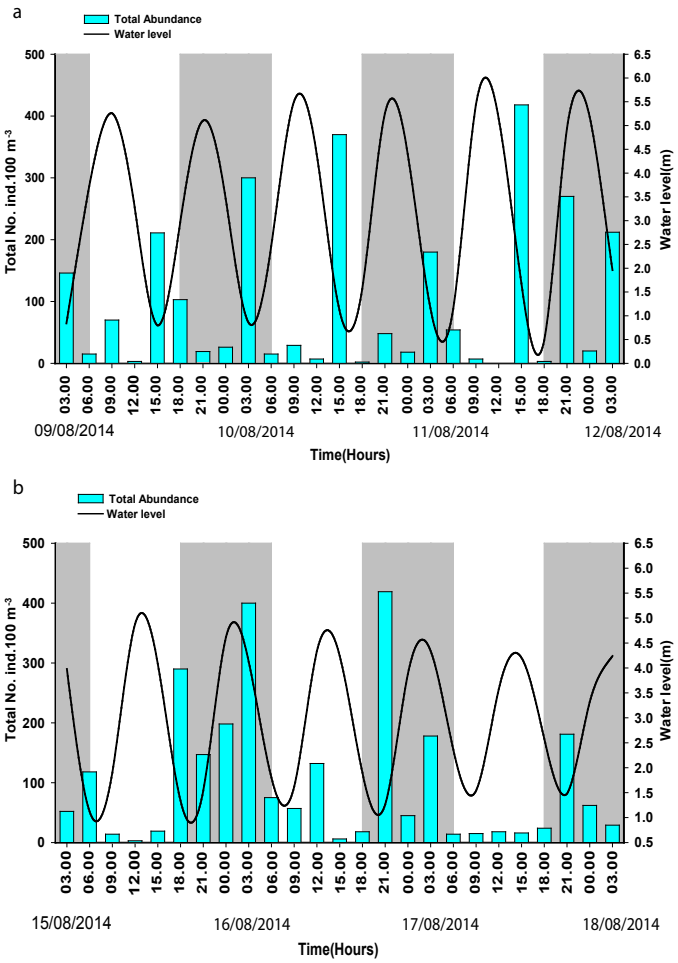


Fig. 13 Diel and tidal changes of total larval abundances of *M. dobsoni* a.spring tide, b. neap tide (Shaded portion indicate the night phase).

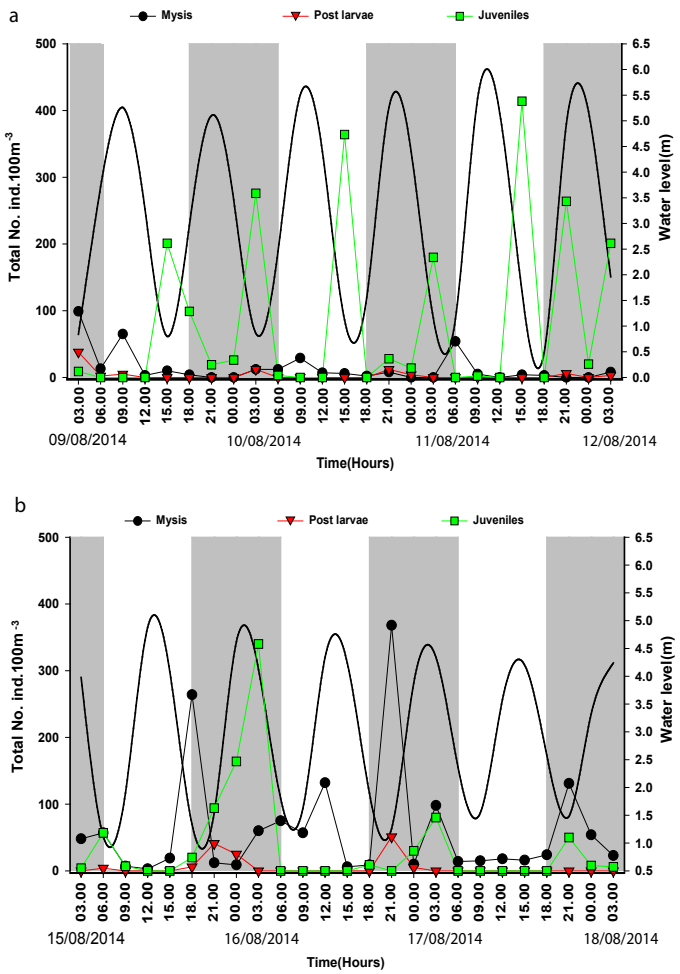
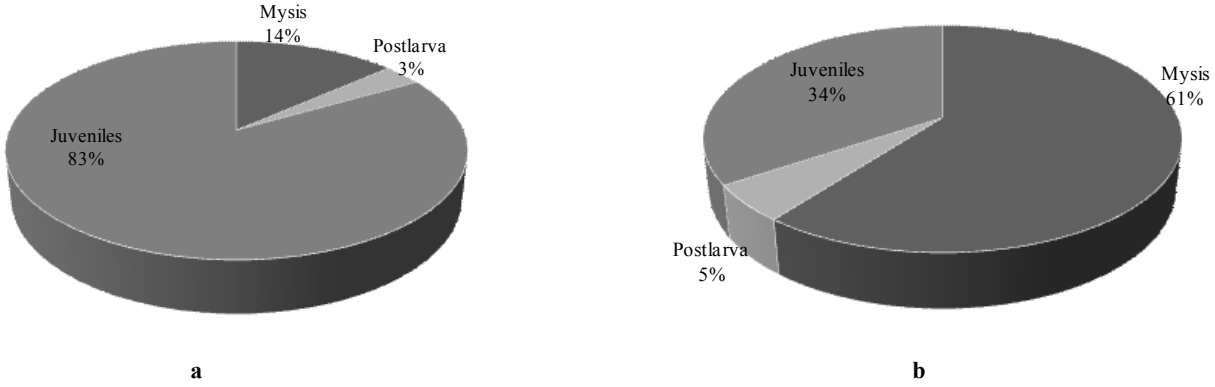


Fig. 14 Diel and tidal changes of different larval abundances of *M. dobsoni* a. spring tide, b. neap tide (Shaded portion indicate the night phase).



a **b**

Fig. 15 Composition of different shellfish larval percentages during **a** spring tide and **b** neap tide

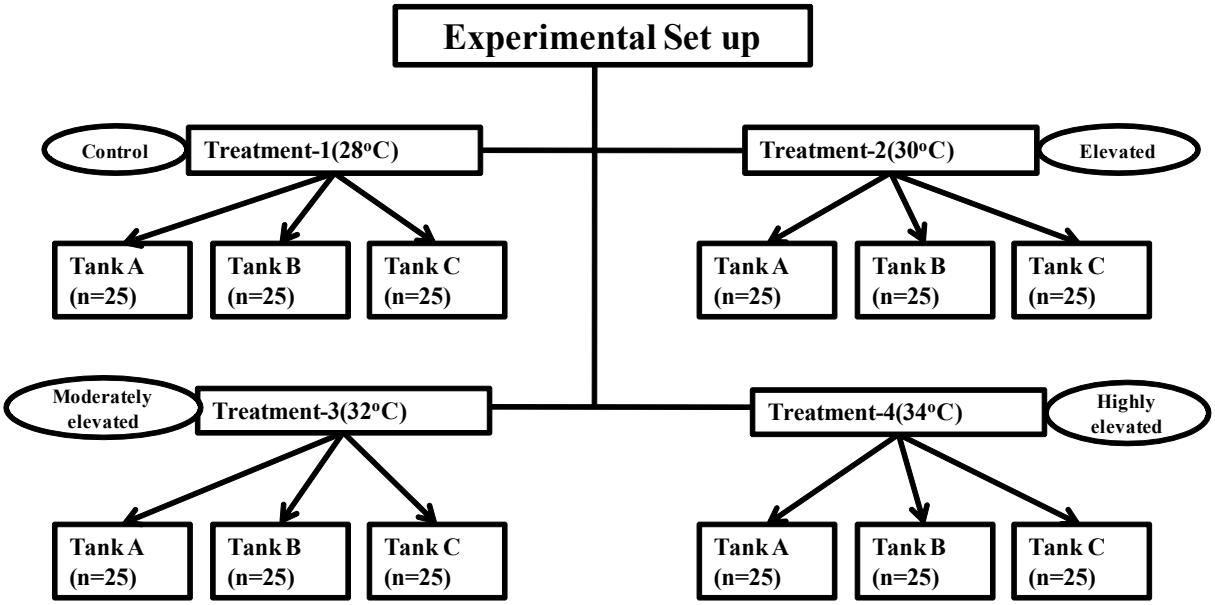


Fig. 16 Schematic diagram of detailed experimental set up during the mesocosm study

Table 9. Characteristics (mean±SD) of seawater used to maintain *Penaeus monodon* individuals during the experimental period in the 25 L tanks.

	Control	Elevated	Moderately elevated	Highly elevated
Water temperature (^{o}C)	28.3±0.2	30.1±0.3	32.2±0.1	34.3±0.2
Dissolved Oxygen (mg.L^{-1})	8.65± 1.02	7.89± 1.36	7.32±1.55	6.89±1.33
pH	8.12±0.05	8.36±0.15	8.05±0.74	7.93±0.32
Salinity	12.56±1.25	12.77±1.96	13.01±1.81	12.48±1.62
Duration of daylight (hours)	12.5±0.5	12.5±0.5	12.5±0.5	12.5±0.5

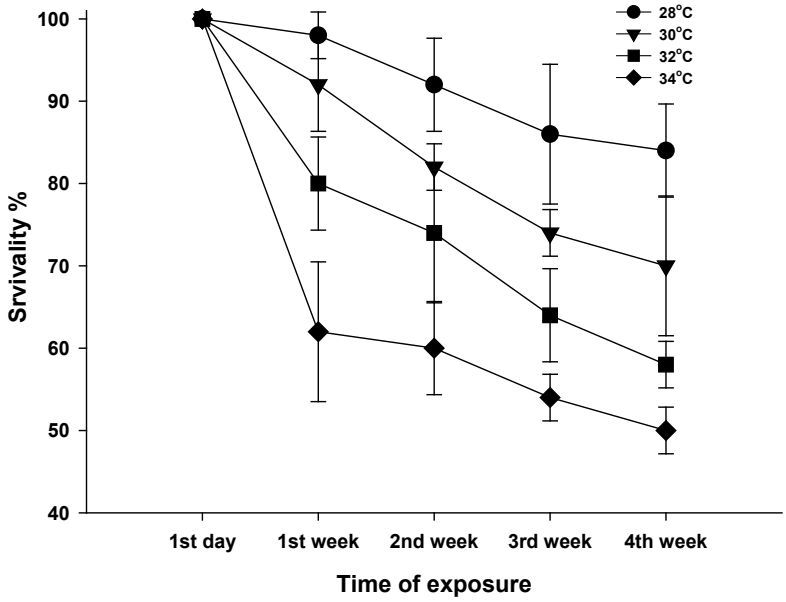


Fig. 17 Variation in survivality percentages at different temperature

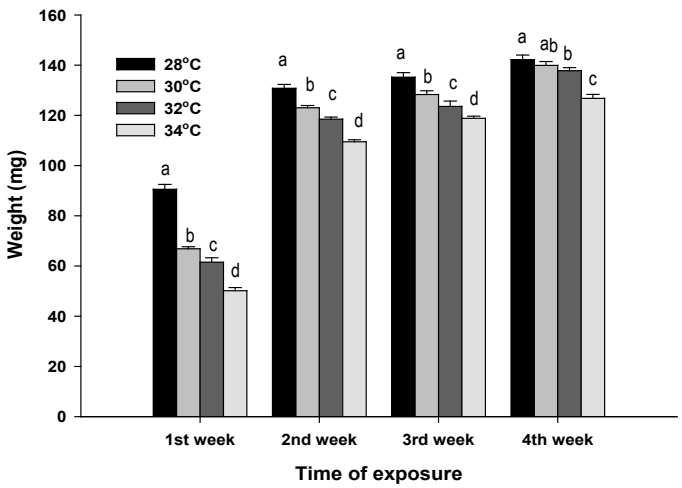


Fig. 18a Changes of body weight with elevated temperature

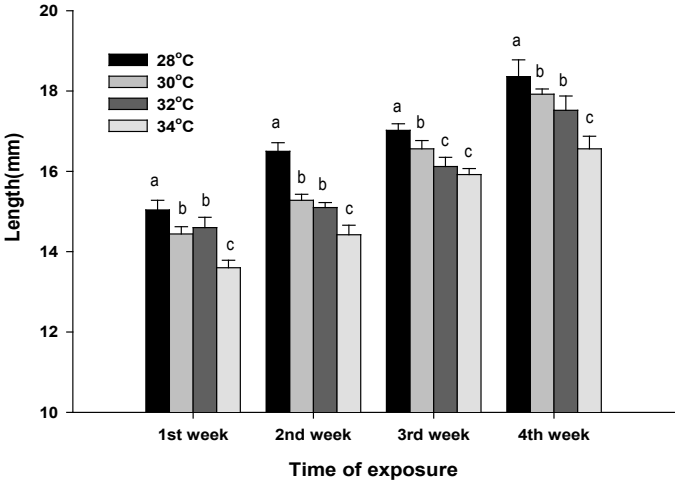


Fig. 18b Changes of length of the body with elevated temperature

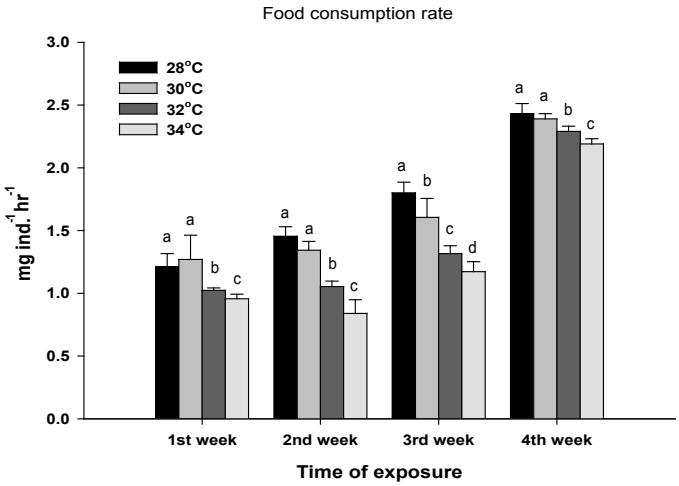


Fig. 19a Changes of FCR with elevated temperature

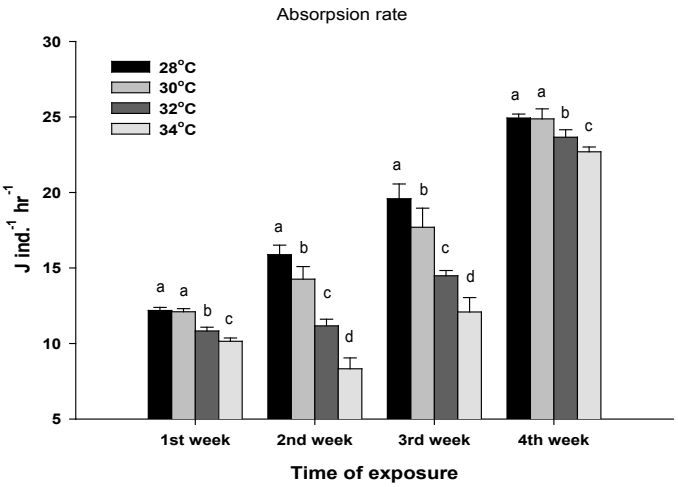


Fig. 19b Changes of absorption rate with elevated temperature

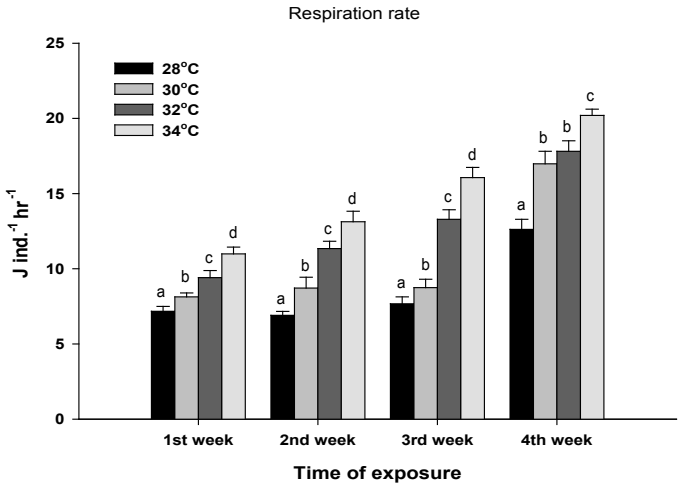


Fig. 19c Changes in respiration rate with elevated temperature

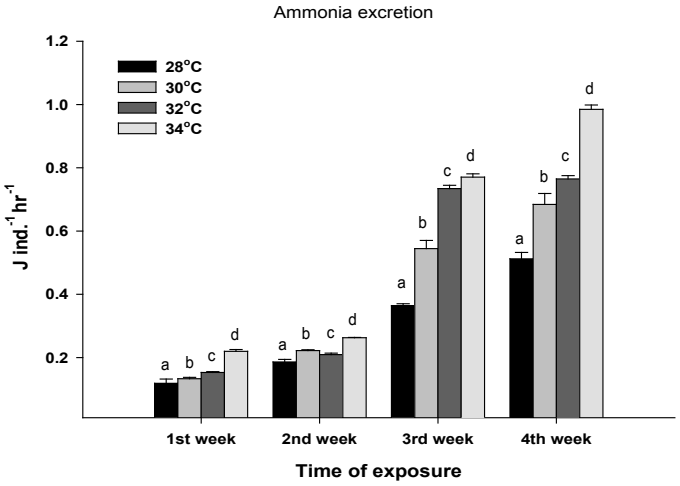


Fig. 19d Changes of ammonia excretion rate with elevated temperature

* Different letters indicate significant difference between treatment groups (p <0.05).

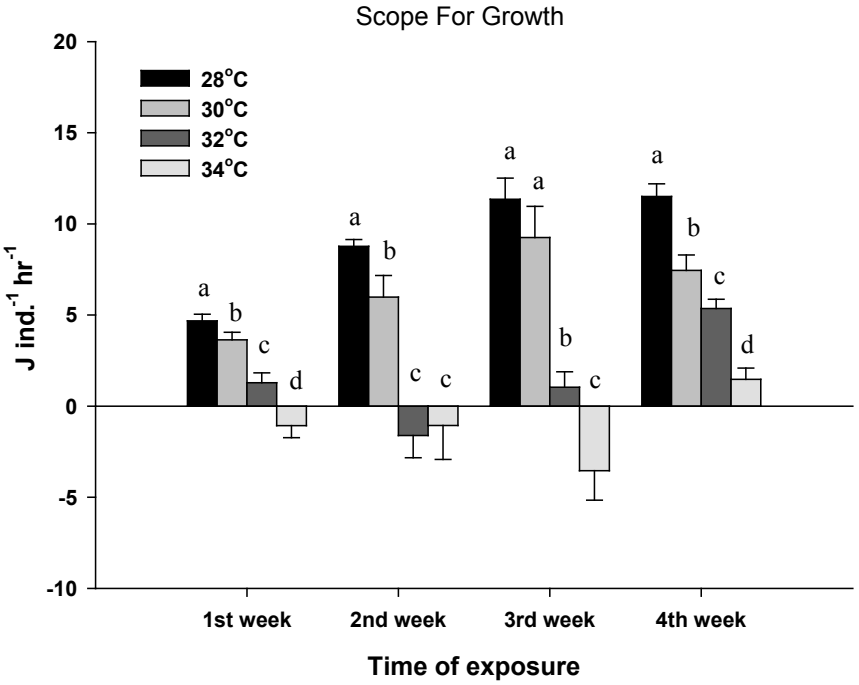


Fig. 20 Variation of Scope for Growth with different temperature treatments
Different letters indicate significant difference between treatment groups (p <0.05).

Table 10. Summary of the main test of PERMANOVA on different physiological variables in shrimp postlarvae exposed to four levels of temperature treatments (28°C, 30°C,32°C and 34°C) on 1st, 2nd, 3rd and 4th week of experiment.

Source of variation	*df*	**Survivality**			**Length**		
		MS	*Pseudo F*	*p(perm)*	*MS*	*Pseudo F*	*p(perm)*
Temperature	3	0.31416	50.582	0.001	3.08E-02	164.86	0.001
Duration	3	8.95E-02	14.403	0.001	0.13051	699.47	0.001
Temperature X Duration	9	2.39E-03	0.38535	0.928	1.15E-03	6.1684	0.001
	df	**Weigth**			**Food consumption rate**		
		MS	*Pseudo F*	*p(perm)*	*MS*	*Pseudo F*	*p(perm)*
Temperature	3	0.21481	999.58	0.001	0.14738	104.4	0.001
Duration	3	2.1989	10232	0.001	0.87527	619.99	0.001
Temperature X Duration	9	4.41E-02	205.33	0.001	1.12E-02	7.9146	0.001
	df	**Respiration rate**			**Ammonia excretion**		
		MS	*Pseudo F*	*p(perm)*	*MS*	*Pseudo F*	*p(perm)*
Temperature	3	1.0398	502.21	0.001	0.1031	1263.4	0.001
Duration	3	1.3383	646.37	0.001	0.78085	9569.1	0.001
Temperature X Duration	9	3.66E-02	17.692	0.001	1.45E-02	178.27	0.001
	df	**Absorption rate**			**Scope for Growth**		
		MS	*Pseudo F*	*p(perm)*	*MS*	*Pseudo F*	*p(perm)*
Temperature	3	0.43344	257.94	0.001	427.34	402.46	0.001
Duration	3	2.0837	1240	0.001	71.3	67.15	0.001
Temperature X Duration	9	5.39E-02	32.046	0.001	23.317	21.96	0.001

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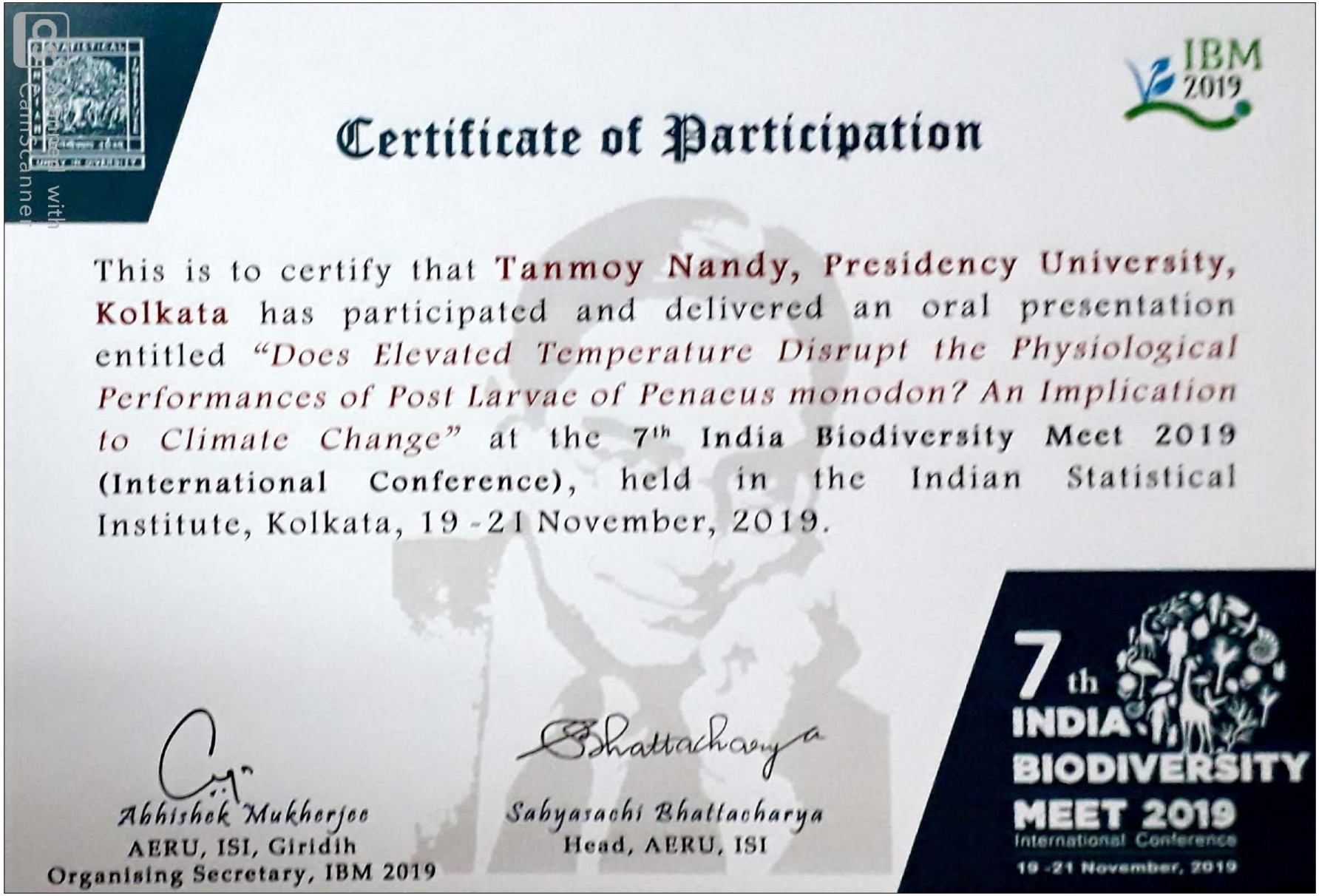

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Intra-monsoonal variation of zooplankton population in the Sundarbans Estuarine System, India

Tanmoy Nandy · Sumit Mandal · Meenakshi Chatterjee

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Abstract The present study was conducted during July 2013 (early phase of monsoon or EM) and September 2013 (later phase of monsoon or LM) to ascertain the intra-monsoonal variation on zooplankton, by selecting 15 study stations in the river Saptamukhi, one of the main estuaries in the Sundarbans Estuarine System (SES). In 2013, SES experienced an unusually high monsoonal rainfall also exacerbated by cloud burst event at Himalayan region (upper stretches of SES) which tremendously increased the river runoff. The present work was aimed to decipher the effect of this unusual precipitation during the monsoon season on zooplankton assemblages along with different hydrological parameters. The abundance of zooplankton was recorded as lower during EM compared to LM. Altogether, 56 zooplankton taxa were identified with copepods forming the predominant population. Thirty-three copepod species were reported with 25 calanoid species forming the bulk of the biomass followed by 5 and 3 species of cyclopoids and harpacticoid, respectively. A combination of multivariate cluster analysis, biotic indices, and canonical correspondence analysis revealed noticeable alterations in the zooplankton community structure across the spatio-temporal scale. Furthermore, significant intra-monsoonal changes in zooplankton population correlated with several hydrological parameters were clearly noticed. *Paracalanus parvus*, *Bestiolina similis* and *Oithona similis* were observed to be the most dominant copepod species in both sampling periods. The result of the present study provides new insight on estuarine zooplankton community after unusual rainfall during monsoon season, and provides further evidence to support the conservation and management of the SES ecosystem.

Keywords Monsoonal precipitation · Zooplankton community · Copepods · Multivariate analysis · Hydrological parameters · Sundarban mangrove ecosystem

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Introduction

Estuaries are the most productive transitional ecotones, characterised by marked gradients of physical, chemical and biological components. Due to the fluxes between ecosystems, estuaries are considered extremely important in terms of maintaining aquatic diversity and providing services to human society (Moderan and Bouvais 2010). They perform several ecological functions and provide permanent and transitional habitats for several fish and invertebrates (Beck et al. 2001).

Zooplankton populations play a key role in pelagic food webs and ecological processes by transferring energy from primary producers to the higher trophic levels, remineralisation of nutrients and regulation of biogeochemical cycles of an estuarine system (Harris

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ORIGINAL RESEARCH ARTICLE

Unravelling the spatio-temporal variation of zooplankton community from the river Matla in the Sundarbans Estuarine System, India

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KEYWORDS
Sundarbans;
Zooplankton;
Copepoda;
Bioindicator;
Seasonal succession

Summary Zooplankton is an important bioindicator of ecosystem functioning. Knowledge of the seasonal fluctuation in the zooplankton population in estuarine waters of the Indian Sundarbans is rather limited. In the present study, we analysed the community structure of zooplankton assemblages and their spatio-temporal variations based on different multivariate statistics and indicator value analysis. A total of 56 taxa were identified and the density was primarily dominated by planktonic copepods and few meroplankton communities during four sampling seasons. The most abundant species were: *Acartia spinicauda*, *Acartia* sp., *Bestiolina similis*, *Euterpina acutifrons*, *Labidocera acuta*, *Paracalanus aculeatus*, *Paracalanus parvus* and *Paracalanus indicus*. Canonical Correspondence Analysis highlighted that temperature, pH, DO, salinity and nutrients were the prevailing environmental parameters associated with significant spatio-temporal changes of zooplankton distribution in this area. The highest abundance of zooplankton was recorded in winter, followed by monsoon, summer and spring. Throughout the study period, different zooplankton indices were observed in good condition. Seasonal occurrence of dominant zooplankton with high *IndVal* index was markedly observed and it might be used as a potential bioindicator for a particular season and environmental condition in this estuarine complex. The results of this study provide evidence for the presence of warm water species in the estuarine waters of the Indian Sundarbans and can be a clear indication of climate change-mediated elevated temperature in the estuarine system. Our results underscore

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ORIGINAL ARTICLE

Short-term variations in surface water properties in the Sundarban Estuarine System, India

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Abstract High resolution measurements were carried out to understand the short-term (<1 h) variability of surface water quality parameters in mangrove-dominated Sundarban Estuarine System of West Bengal, India during flood phases of spring-neap tidal cycle in a peak monsoon season August 2014. We observed that tidal propagation of both phases strongly influenced the water quality properties. During spring tide salinity, DO, pH, nitrate, phosphate, silicate, chlorophyll *a* and phaeopigments concentration exhibited increasing trends; whereas at neap tide nitrate, ammonia and chlorophyll *a* showed decreasing trends. Average nutrient concentrations were much higher during neap tide than spring tide. All the measured water quality parameters varied in every 15-min interval influenced by the tidal current, mangrove litter fall, re-suspension of bottom sediment and river runoff. The effect of tidal amplitude was observed to be the important factor in determining the variability in most of the water quality parameters.

Keywords Sundarban Estuarine System · Water quality · Monsoon · Spring–Neap Tide

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Introduction

Estuaries play an important role in biogeochemical cycle because of their capability to regulate a huge amount of river-borne major and minor elements entering the coastal environment. Estuarine ecosystems are complex, dynamic and experience strong gradients in water quality properties and complex hydrodynamic processes (Mitra et al. 2011). The distribution of nutrients and other environmental parameters in estuarine waters plays pivotal role in controlling biogeochemistry of estuaries. The Sundarban Estuarine System (SES) is a unique ecosystem, covered by mangrove vegetation which is very much tidally induced and all parts of the SES are propagated by the dominated semi-diurnal tide with an overall northward amplification (Chatterjee et al. 2013). Different physico-chemical parameters such as salinity, pH, dissolved oxygen (DO), chlorophyll and some essential micro-nutrients (N, P, S) are very much significant in controlling the productivity of estuarine system (Manasrah et al. 2006; Nixon et al. 1986). This mangrove-dominated estuarine region also provides major pathways for nutrient recycling and acts as a natural filter for pollutants coming from the human settlements and industrial area in its northern part. Measurements at hourly intervals or time series study are more common practice to study the changes in properties with diurnal and/or tidal variability, but sub-hourly changes of such environmental parameters have not been done earlier from this region, though Anand et al. (2014) had been reported variations in sub-hourly biogeochemical properties from Zuari estuary, central western part of India. The sub-hourly sampling strategy in an estuarine system is very essential to understand the intra-tidal variability of nutrients and the effect of tidal straining and suspended sediment on water column stratification (Uncles 2002). Cassidy and Jordan (2011)